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THE PYRITIC DEPOSITS OF HUELVA, SPAIN.

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PART II.[1] ORE DEPOSITS.

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ORE-DEPOSITS.

The zone or belt of pyritic masses for which the region is famous, and which alone are considered in this work, constitutes only a restricted portion of a much larger area embracing all the

[1] The first part of this paper dealing with the geology of the region appeared in Volume V., No. 4, of this journal, pp. 357 to 372.

southern part of the meseta, and characterized in general by quartz veins with ores of copper and some lead, zinc and antimony. These have seldom been worked to advantage. Further, the Huelva and adjoining districts carry also abundant deposits of manganese ore, which have been exploited, often with much success, during the last fifty years. References to these are given in the bibliography.

In describing the sulphide deposits, the term lode is here used, since, in the writer's opinion, it indicates the origin of the deposits, as well as their structural features. The word is, indeed, generally used, and with full justification, among the miners.

Structural Relations.—The pyritic deposits occupy a belt extending from Aznalcollar in Sevilla, through Huelva, to Aljustrel in Alemtejo (Portugal). Their apparent distribution in long belts is purely fortuitous, and due to the tectonics of the district, but, on a smaller scale, well-marked lines of mineralization are evident, extending over two or three miles, and including several detached lodes. This is to be expected, if the deposits occur in extended shear-zones. A group of lodes may be arranged either in series or in parallel. In the former case, a line of disconnected masses succeed one another along the strike; in the latter case, the lodes are found close together on parallel lines of strike, and often arranged *en echelon,* when viewed in vertical section. In such cases one lode may outcrop, while its neighbor does not.

In form the lodes are lenticular, both in plan and in section, but their dimensions are variable, and there are all gradations from very elongated lenses, to short wide masses. A type sometimes met with is wedge-shaped in plan, with one broad and one tapering end. As a rule, however, both ends of a lode feather out along the strike. "Rolls" may occur along the walls, and the lodes frequently divide up into stringers, both at their terminations in strike, and vertically. Their lower ends generally taper to a point in cross-section, accompanied often by a decrease in length at successive levels; but occasionally they have a broad base, especially when, like the north lodes of Rio Tinto (Fig. 41, p. 423), they are enclosed in porphyry. A pitch along the strike of the lodes is occasionally seen.

The deposits show great variations in size, but there is a general tendency towards proportional dimensions in individual lodes. The longest masses include the San Dionisio and South Lodes of Rio Tinto, which have a combined length of over 2 kilometers. La Zarza is 1,250 meters in length, and the lodes of Sotiel cover a length of over 1,000 meters. The great majority of the lodes, however, vary between 300 and 700 meters, and a few are shorter than 200 meters. The width, *i. e.*, maximum width, of lodes is generally proportional to their length, but there is considerable irregularity. San Dionisio, probably the largest single lode in the field, reaches a width of 250 meters, but the majority of the larger lodes range between 50 and 150 meters wide, and the smaller ones between 15 and 30 meters.

The depth or vertical extent of lodes is, in the first place, roughly proportional to their other dimensions. Thus San Dionisio is opened up to a depth of 500 meters and is known to extend still deeper. This is, however, an exceptional figure. The vertical range of ore deposition has undoubtedly been very restricted, and has probably in no case exceeded 1,000 meters. Few of the lodes appear to have exceeded an original depth of 500 meters, and as a result of denudation, very few now attain to 300 meters. The smaller lodes invariably taper out at a much less depth than this. The factor of denudation has, however, been the all-important cause in determining the present vertical extent of lodes in the field. This is strikingly seen where two or more parallel lodes occur *en echelon*. In such cases, one lode may feather out a short distance below its outcrop, while its neighbor has no outcrop, but dies out before reaching the surface (Fig. 44, p. 428). The extreme effect of denudation occasionally seen has been the erosion of a lode to such an extent that the residual portion has been completely converted into gossan, with no sulphide ore beneath. On the other hand, many lodes taper near the surface, and have an insignificant outcrop, thus indicating that but little has been removed by erosion. While surface erosion has undoubtedly removed much ore from the lodes, it is worthy of note, more especially in view of the restricted vertical range of ore deposition, that but for

this factor the pyritic zone would not be exposed today, nor its existence indicated.

Lode-walls and Lode-channels.—The lodes as a whole "conform" with the bedding of the enclosing rocks when these are slates. There are, however, frequent local exceptions, where the planes of bedding may be seen to be crossed by the wall of a lode in some parts of its course. This is seen when the wall is marked by bulges or rolls, or where the slates have been contorted. Professor Klockmann does not consider that such phenomena have ever been shown to exist among these lodes,[1] but the writer observed the lode walls cutting across the slates in certain parts of both Santa Rosa and Sotiel mines, and in these cases it was significant that the cleavage planes crossed the bedding planes, and the lode walls followed the lines of cleavage (Fig. 33. See previous issue, No. 5, p. 70). Such local irregularities are characteristic of bedded or "segregated" lodes, and the fact that the lodes as a general rule follow the bedding of the rocks cannot be regarded necessarily as an argument for a syngenetic origin.

The lode walls are generally well-defined and smooth, and marked by clay selvages or gouge. Slickensides are common, and the walls are in all respects similar to those of veins of the normal type. They clearly mark planes of former movement. The adjoining slates are frequently much crushed and contorted, especially along the continuation of the lode channel, and brecciation of the rocks, with a cement quartz and massive pyrite, is sometimes seen, especially where the lodes adjoin porphyry, as at Rio Tinto, or diabase, as at Santo Domingo.[2]

It is characteristic of the lodes that they are invariably found along planes or zones of weakness, such as the contact of porphyry and slate, or quartzite and slate. The lode zone of Cabezas del Pasto, for example, is in a belt of soft crushed slates some 50 meters wide, with quartzites to the south of it, and greywacke to the north. The position of the lodes throughout the area has clearly been determined in each case by structural fea-

[1] *Zeits. f. prakts. geol.*, X., 1902, p. 113.
[2] L. de Launay, *Ann. d. Mines*, ser. 8, XVI., 1889, p. 471.

tures, *i. e.*, by natural lines of weakness which gave way under strain and permitted shearing or overthrusting.

The Country Rock.—Of the 33 chief lodes or groups of lodes in the district, 4 are practically enclosed in porphyry, 2 are at the junction between slate and diabase, 11 are at the junction of slate and porphyry, and 16 are enclosed wholly in slates or associated sedimentaries. A consideration of their structural relations, indeed, at once suggests that the lodes cannot be regarded as genetically related to any one group of igneous rocks *per se*.

Beyond the walls, the country rock is impregnated with pyrite to a distance of from 10 to 40 meters, according to the size of the ore body, and the effect is commonly greater on the hanging wall side. The adjoining rocks further show the effects of hydrothermal action to a marked degree, forming the zone of "salbanda." At San Dionisio, Rio Tinto, the porphyry has been altered, over a distance of 10 to 20 meters from the wall, to an earthy porous rock, full of unaltered quartz phenocrysts. Under the microscope, the hydrothermal changes can be clearly seen *superimposed on the previous granulation and sericitization in the shear zone.* Abundant chlorite and carbonates have been developed, and magnetite is altered to pyrite and siderite. The rock becomes an aggregate of quartz, sericite, chlorite and carbonates. The following analyses show the changes of the different constituents:

	Fresh Porphyry (San Dionisio).	Altered Porphyry (San Dionisio).
H_2O +	0.18	0.23
H_2O —	0.35	1.41
SiO_2	76.21	70.68
Al_2O_3	12.66	11.45
Fe_2O_3	2.98	1.31
FeO	1.46	0.72
CaO	1.15	2.28
MgO	0.10	0.17
K_2O	3.27	4.85
Na_2O	1.64	0.65
FeS_2	—	1.27
MnO	0.08	0.05
CO_2	0.09	5.08
Total	100.17	100.15

It thus appears that the rock has undergone a notable addition of carbon dioxide, a concentration of potash, and a corresponding loss of soda. Silica has been somewhat reduced, and the loss of iron oxides is in part accounted for by the formation of pyrite. The changes are such as would be effected by solutions of alkaline sulphides and carbonates, and are in every way similar to the metasomatic processes which have been studied in normal veins.

Lodes Structure.—The typical lodes are composed of massive, homogeneous pyrite. The ore is remarkably free from admixed county-rock. Enclosed "horses" of country rock (*cuñas de esteril*) occur, but they are unimportant in comparison with the width of the lodes. At other times, the lodes are frequently split up into legs or strings by intercalated seams of country rock. Later faults are not common, except in the case of some small lodes, where considerable displacement and even severance of the lode has occurred. That movement has occurred since lode-formation is, however, clearly shown by the abundant and often characteristic joints which traverse the mass of the ore. Thus a set of vertical joints is commonly seen running parallel with the strike of the lode, and frequently a second vertical set, running from wall to wall and passing into the country-rock, may occur. Finally, horizontal joints or "floors," and irregular diagonal jointing, are sometimes present. The joint planes are nearly always well slickensided, and often lined with quartz. The comparative absence of faults in the lodes is probably due to their massive and resistant nature.

The typical ore is seldom conspicuously banded in structure, but highly banded ores occur as local seams in parts of the lodes, alternating with and sometimes passing insensibly into the massive ore. A faint banding can, however, generally be discerned; and the planes of banding are, in all cases, parallel with the lode walls.

A subordinate but characteristic type of ore body is the zone of cupriferous or pyritous schists. This consists of a belt of more or less altered and contorted slates, often of considerable width, and heavily impregnated with pyrite and chalcopyrite.

The ore of these zones is, indeed, often richer in copper than that of the neighboring massive lodes, with which they are generally associated. A good example is the Esperanza lode at Tharsis, described by C. F. Courtney.[1] The walls of these lodes are ill-defined, but clearly mark the boundaries of zones of shearing or crushing, and the highly slatey ore shows every transition, first, to the banded type of ore, and secondly, to the massive granular pyrite in which almost every trace of banding is lost. Seams of this ore frequently occur within the wider zone of impregnated slates. These zones are of very considerable importance in the evidence that they give of the structure of the ore.

THE ORES.

The Gossan.—The essential ore of the oxidized zone is a massive hematite, containing over 50 per cent. of iron, and from 10 to 15 per cent. of siliceous and argillaceous matter. Its depth varies from 25 to 50 meters, the average being about 30 meters. The depth of oxidation has clearly been determined, in all cases, by the topographic level of ground water, though it is dependent also, in a minor degree, on the relative porosity of the enclosing rocks. The appearance of the outcrop is often somewhat deceptive; thus in the case of lodes whose upper termination does not reach the present surface, the line of outcrop may be marked only by ferruginous slates, or there may even be no surface indication whatever of ore beneath. Again, as already pointed out, there are one or two bold outcrops of gossan in the field, which represent the oxidized root of a lode and carry no ore beneath them. These two cases, of course represent the two extremes between which nearly all the deposits lie.

The lower limit of the gossan is sharp and well-defined, and the line of contact between gossan and sulphide ore is sometimes marked by an earthy zone carrying considerable values in gold and silver. This has been described by J. H. L. Vogt[2] who has pointed out that it represents a concentration during secondary enrichment, of the traces of gold and silver in the original ore,

[1] *Proc. Inst. Civ. Eng.*, CXXV., 1896, p. 128.
[2] *Zeits. für prakts. geol.*, 1899, p. 250.

the precious metals dissolved in ferric sulphate being precipitated by the reducing influence of the pyrite. This concentration of gold and silver was well shown at San Dionisio (Rio Tinto), and at Angostura (Esperanza), the ore of the former lode giving an assay of £7 10s. 0d. per ton. An analogous but much more important zone of precious metals has been described by H. H. Knox from the pyrites deposits of Koninkhoff, Perm.[1] A noteworthy feature of the oxidized zones of these lodes is the absence of oxidized ores of copper, except as mineralogical curiosities. This poverty is doubtless due to the strong reducing influence of the sulphide ore.

All the facts of occurrence of the gossan, and the factors to which its depth and its varying character are due, leave no doubt that throughout the field it is the result of normal processes of oxidation. No theory of reaction between ascending iron-bearing solutions and descending surface waters is in the least degree applicable to the iron hat of the Spanish pyrites deposits.

The hematite deposits of the mesa de los Pinos and other localities around Rio Tinto have been investigated by several writers.[2] They are shallow deposits, averagings 3 or 4 meters in thickness, and contain Miocene plant remains. They have been shown to be lake or bog ores deposited by streams draining from the neighboring lodes, the present occurrences being remnants of denudation left as cappings on the hills.

Zone of Enriched Sulphides.—The top portion of the sulphide zone for a thickness of a meter or more is generally composed of leached or impoverished pyrite, containing only traces of copper. There is thus a zone of impoverishment similar to that described by H. H. Knox from Koninkhoff[3] and by Max Boehmer from Leadville.[4]

Beneath this commences the zone of enriched sulpides, in which the ore assays from 3 to 12 per cent. of copper, the aver-

[1] *Trans. I. M. M.*, XVIII., 1909, p. 273.

[2] J. Arthur Phillips, *Quart. Journ. Geol. Soc.*, XXXVII., 1881, p. 1. E. Cumenge, "Notes Sur Rio Tinto," Paris, 1883. J. H. Collins, *Quart. Journ. Geol. Soc.*, XLI., 1885. J. Gonzalo y Tarin, *loc. cit., sup.*, Vol. II., 1888, p. 587.

[3] *Loc. cit., sup.*

[4] Econ. Geol., III., 1908, p. 337.

age being from 4 to 7 per cent. The enriched pyrite, which is softer and more porous than the lean ore beneath, carries chalcopyrite and chalcocite as the chief products of enrichment. The development and paragenesis of these sulphides will be described later, when dealing with the microstructure of the ore. Both chalcopyrite and chalcocite (*negrillo*) are abundant in the upper part of the zone, as veins filling cracks in the ore and in the adjoining country rock. Bornite is not very characteristic, but strings of argentiferous galena, with occasional tetrahedrite and other silver-bearing ores, have been abundant as secondary products in some lodes. Gypsum and barytes occur with the secondary ores, filling fissures and joints. Native copper occurs in small quantities, in arborescent form, and also deposited on old mine timbers. Various other secondary ores have been recorded, among which may be mentioned the anglesite of Santo Domingo.[1]

Owing to the imperceptible transition from enriched to lean ore, the depth of the zone of enrichment cannot be very exactly stated, and, where faults or fissures occur in or adjacent to the lodes, there may result local enrichment at much more than the usual depth. The average depth of enrichment may, however, be placed at 50 to 60 meters below the gossan, or 80 to 100 meters below the outcrop. To this depth the ore will in most cases, be found to assay 3 per cent. or more in copper.

In many cases, as has been pointed out by Wetzig[2] there is undoubtedly a relation between the depth of enrichment and the thickness of the overlying gossan. Thus at Rio Tinto and Sotiel, where the gossan is from 25 to 35 meters thick, enrichment has in general been effective for a further 70 or 80 meters at least. On the other hand, at Herrerias and Cabezas del Pasto, where the lodes taper towards the surface and have a shallow gossan, the zone of 3 per cent. ore does not extend below about 40 meters from the surface. This relation is in accordance with the known facts of enrichment by descending waters and emphasizes still further the importance of prolonged erosion in influencing the economics of this field.

[1] R. H. Solly, *Min. Mag.*, VII., 1887, p. 61. A. La Croix, *Ann. d. Mines*, ser. 8, XVI., 1889, p. 474, note.

[2] *Zeits. für prakt. geol.*, XIV., 1906, p. 180.

Zone of Primary and Lean Sulphides.—With increasing depth the copper content, first of the enriched ore and later of the primary ore, progressively decreases, a fact first emphasized by J. H. Vogt. The bulk of primary ores vary between .8 and 2 per cent. of copper, while some, such as those of El Perrunal and La Zarza, assay .5 per cent. or less. The rate of decrease in depth varies greatly. In the low-grade masses, there may be comparatively little change to considerable depths. The Tharsis lodes, on the other hand, were characterized by rapid impoverishment, while the reverse is true of San Dionisio. At Santo Domingo the rate of decrease, over both secondary and primary ore, is about .5 per cent. in 40 meters vertical. At Herrerias the ore at a depth of 60 meters assays only 1.5 to 1.8 per cent, while at the neighboring mine of Cabezas, the ore averages 2 per cent. at 80 meters depth.

While the general law of decrease in depth holds good, there are local exceptions. In several mines there have been found patches of rich primary ore (chalcopyrite) at or near the lower terminations of the lodes. This was the case in certain parts of Santa Rosa (Fig. 44, p. 428), Sotiel, La Zarza and other mines.

As regards the distribution of the copper content of the ore in the form of ore shoots, evidence is not easy to obtain, as there are no marked variations, and the copper content is so low as to make detection of shoots difficult. Nevertheless, some undoubted instances were seen, during the writer's examination, of shoots of ore. In these shoots, the copper-content averaged 2 per cent. or more, while the lower grade ore outside the limits of the shoot assayed from .5 to 1 per cent. At times an ore shoot occurs along either the foot wall or the hanging wall, with lean ore in the center of the lode. As a general rule, however the tendency is for the better values to be concentrated in the center of the lode, while the ore becomes leaner on approaching the walls (Fig. 43, p. 426). There is, in this, some analogy with the deposits of Copperopolis, Cal., where John A. Reid has pointed out that the ore is richer in the center of the lodes.[1]

None of the lodes examined show any variation in the rate

[1] Econ. Geol., II., 1907, p. 413.

of decrease of copper content, according to the amount of dip, such as has been pointed out by H. Sjögren at Röros and Sulitjelma.[1] The inclination of all the Huelva lodes is generally pretty steep and varies but little in different parts of the field. Differences in the rate of decrease due to this cause, if they exist, are consequently not easily detected, and in any case are not likely to be of economic significance.

The primary ore may be considered under four classes, namely, massive ore, banded and complex ore, pyritous slates and magnetic ore. The massive ore, in which, it should be noted, a faint trace of banding is very frequently discernible, constitutes the great proportion of the lodes. It has a specific gravity of 4.5 to 4.8, and carries from 48 to 50 per cent. of sulphur. As the copper content decreases, the ore becomes harder and whiter. The total amount of silica, alumina and earths seldom exceeds 3 or 4 per cent., except in local siliceous ores. Lead and zinc occur in small quantities. Arsenic varies from .25 to 1 per cent., and traces of bismuth, selenium, tellurium and other metals are present. Silver occurs in quantities up to 1 or 1.5 ozs. per ton and the gold amounts to 1 or 2 per cent. of the silver present. Analyses of typical ores are given in the works of Vogt, De Launay, Collins and Gonzalo y Tarin.

The banded ores occur locally in portions of the lodes or occasionally constitute the whole mass of some small lodes. The feature of these ores is the individualization of the constituent minerals in parallel seams. Their copper content is frequently high, rising to 5 per cent. or more at times, without enrichment. They generally carry from 5 to 10 per cent. of each of galena and blende, and are often highly siliceous, the silica percentage ranging up to 25 per cent. A local variation of the complex ore is a massive granular "bluestone," composed of galena and blende in varying proportion, with smaller quantities of pyrite and chalcopyrite.

The pyritous slates are characterized, as already mentioned, by a large proportion of siliceous and argillaceous matter, and frequently by a copper-content higher than the massive ore. In this respect they are comparable with the banded ores.

[1] Econ. Geol., III., 1908, p. 637.

Deposits of magnetic ore occur at Cala, near Santa Olalla and elsewhere in the province. The Cala deposits have been described by Schmidt and Preiseverk.[1] The ore beneath the hematite gossan is composed, in different masses and in varying proportion, of magnetite, pyrrhotite and cupriferous pyrite. As the above mentioned writers have emphasized, the consideration of this type of ore body is of great importance in connection with the problem of genesis of the deposits of the region.

Deposition of the Ore.—Both field evidence and an examination of thin sections of the different ores go to support the conclusion that in these lodes the ores have for the most part been formed by replacement of zones of sheeted and crushed rock.

Field Evidence.—The lodes are devoid of comb structures or vughs, such as have been found in some of the Norwegian deposits. Enclosed horses of slate are obviously unreplaced remnants of the original crush zone, and not fragments of rock broken off and enclosed in the ore as it was deposited. In the three commonly occurring classes of ore, there is clearly to be seen, as already stated, a gradual transition from pyritous slates through banded complex ore, to more faintly banded ore, and finally to the massive ore in which all trace of banding is lost. Concomitantly with these changes, the percentage of siliceous and earthy constituents gradually decreases. The banding is everywhere parallel to the lode-walls.

Microscopic Evidence.—In thin sections of the ores, the gradual changes can be still more clearly followed. In the slates the pyrite appears in strings of scattered granules and crystals, which gradually replace the constituents of the slate along the bedding planes, and unite to form parallel seams of granular ore alternating with seams of unreplaced chlorite, sericite and quartz (Fig. 36, p. 415). As the change proceeds further, and more especially when the slates, as is very often the case, are highly crushed and contorted, the ore gradually forms a compact aggregate of interlocked crystal grains, and this aggregation finally obliterates all trace of the original bedding planes of the slates (Fig. 37, p. 416). The absence of banding in the great bulk of

[1] *Zeits. für prakt. geol.*, XII., 1904, p. 225.

the ore is thus accounted for; the process of replacement, as a general rule, tends to destroy, rather than to preserve, the lines of bedding. At times, however, traces of banding are still preserved in the massive ore, in the alignment of residual quartz grains and strings of sericite, both of which minerals are always present in small quantities. In some specimens of ore from the North Lode of Rio Tinto, which is enclosed in porphyry, residual

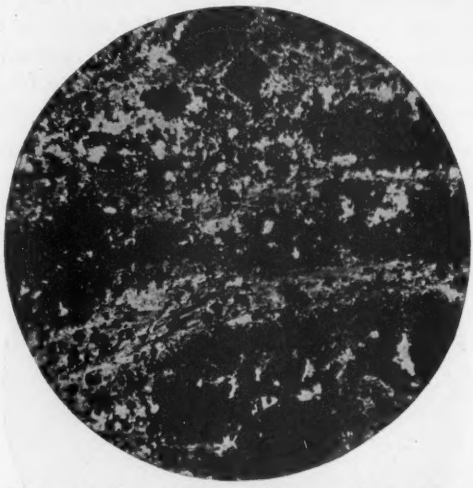


FIG. 36. Slate or phyllite partially replaced by pyrite, forming a banded ore. The colorless portions are quartz and the grey bands are of sericite along the bedding (and cleavage) planes. "Five per cent." lode, Sotiel. × 50.

(corroded) quartz grains were observed, identical with the quartz crystals in the adjoining porphyry, and indicating that here also the ore had replaced the crushed rock.

In the banded ore thin seams of closely packed sericite aggregates and quartz grains alternate with the seams of sulphides, and the structure of the rock is here well preserved. The striking difference in character, however, between these ores, in which the different sulphides are more or less separated, and the massive ore, in which the sulphides constitute practically a homo-

geneous aggregate, must have involved the action of some additional principle. It may have been due in part to differences in the nature of the country rock, while the separation of the sulphides indicates that the respective osmotic pressures of the different sulphides in solution were effective during ore deposition.

The available evidence strongly supports the hypothesis of replacement. At the same time, it must be pointed out that the persistent lenticular form of the lodes suggests the formation of fold cavities or fault slip cavities. The nature of the movements, indeed, along slip planes, probably resulted in such cavities, these being, however, filled, as they were formed, with crushed or sheared rock, prior to the advent of the ores. That

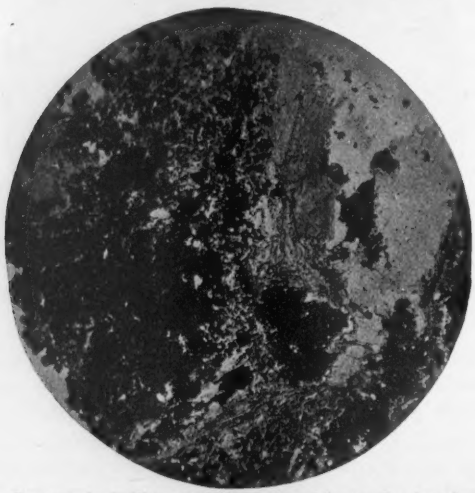


FIG. 37. Contorted phyllite partially replaced by pyrite forming a massive granular ore. The rock is composed of an aggregate of sericite fibers, and the replacement-ore is devoid of any banded structure. "Five per cent." lode, Sotiel. × 50.

practically all the ore of the lodes has been formed by replacement of rock, the micro-structure leaves little room for doubt.

Microstructure—Paragenesis and Secondary Enrichment.—In order to study these problems, a series of selected specimens

were polished and examined by reflected light, the general procedure following that of the recent researches of W. D. Campbell and C. W. Knight, and of James F. Simpson.

In the lean primary ore the copper is present as chalcopyrite, in minute scattered grains, or as threads and strings traversing the granular pyrite and filling interstices in the ore. When the ores assay .5 per cent. or less of copper, the mineral is extremely fine and requires high powers for its detection. When the ore is richer, the chalcopyrite occurs as interlacing strings running through the ore, and wrapping round crystal-grains of pyrite. It may also form irregular branching masses, enclosing earlier formed grains and crystals of pyrite. As a general rule, the chalcopyrite belongs to a later stage of deposition than the pyrite.

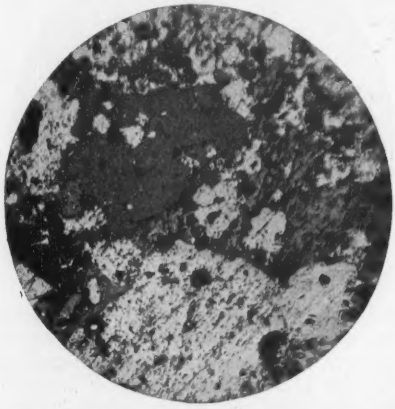


FIG. 38. Enriched ore, San Dionisio, Rio Tinto. Depth 200 meters. In the center of the figure is a mass of secondary chalcocite, the rougher stringy mineral around it being chalcopyrite, embedded in the pyrite. The chalcopyrite is here partly of secondary origin, and is altering to chalcocite. × 100.

When blende is present it forms strings or small bunches traversing the ore, and when present in quantities up to 8 per cent. or more of zinc, it occurs in masses wrapping round grains of both pyrite and chalcopyrite. It is clearly later than both these. Galena occasionally seen, is generally associated with

blende, and may be either intergrown with or deposited round this mineral.

In the complex banded ores pyrite and blende frequently occur in alternate seams, the pyrite being traversed by parallel strings of chalcopyrite, while the blende is accompanied by more or less galena. The blende and galena likewise enclose granules of chalcopyrite. When pyrite is present only in subordinate quantity, it occurs as scattered grains enclosed in seams of the other minerals, chiefly chalcopyrite.

The granular lead zinc ore shows an aggregate of galena and blende, the latter forming a cement and filling interstices in the

FIG. 39. Enriched ore, San Dionisio, Rio Tinto. Depth 100 meters. The specimen shows a mesh of secondary chalcopyrite gradually replacing the light-colored pyrite. The black portions are cavities in the ore, filled with dust during the polishing. × 100.

earlier blende, while the latter encloses scattered crystals of still older chalcopyrite.

The order of deposition of the various primary sulphides has been, in general, pyrite, chalcopyrite, blende, galena.

The processes of secondary enrichment, as seen under the microscope, are of two types. There may be, on the one hand, a direct change from chalcopyrite to chalcocite, with progressive

aggregation of chalcocite, or, on the other hand, a gradual deposition of secondary chalcopyrite, accompanied by replacement of pyrite, and a subordinate development of chalcocite. The latter mineral is recognized by its dull-gray color and smooth surface, and by etching with dilute nitric acid.

In the first case (Fig. 38, p. 417), the chalcocite appears as a selvage to the grains of chalcopyrite, or as an alteration product of thin strings of the primary mineral. It gradually increases till it encloses only a residual core of chalcopyrite, which finally disappears altogether. The grains of chalcocite thus formed act as centers, round which larger masses gradually grow, spreading into and replacing the surrounding pyrite along the minute cracks, pores and solution-cavities in the ore.

In the second type of enrichment (Fig. 39, p. 418), there is a simple aggregation of chalcopyrite by deposition of the secondary around a nucleus of the primary mineral, the two being indistinguishable. Stringy masses of chalcopyrite are thus formed, which continually replace the pyrite, until the ore contains compact bunches of chalcopyrite scattered through it. In this case, the formation of chalcocite is subordinate till a comparatively late stage, when it goes on as before, appearing first as a selvage round the masses of chalcopyrite and gradually spreading into the interior. Bornite occurs in both these cases, as thin veins apparently intermediate in point of formation between chalcopyrite and chalcocite, but it is very subordinate in quantity.

As regards the conditions which determine one or other of these two processes of enrichment, the direct formation of chalcocite appears, from the writer's specimens, to be characteristic of lean ores, and often occurs at considerable depths. On the other hand, the deposition of secondary chalcopyrite was observed chiefly in the upper parts of the zone of enrichment and in richer primary ores (1.5 to 2 per cent. or copper). Thus, some specimens from a depth of 300 meters in San Dionisio showed the direct formation of chalcocite, while rich specimens from higher parts of the same lode showed abundant formation of secondary chalcopyrite, with only a subordinate amount of chalcocite forming round this.

The deepest ore in which enrichment was observed was that from San Dionisio (300 meters). No percentage enrichment of this ore, however, is indicated by analysis, the two specimens which showed the alteration assaying only .55 and .85 per cent. respectively of copper. The observation shows, however, that the preliminary stages of enrichment begin at much greater depths than the generally assumed lower limit of the enriched zone of the lodes. It also indicates the difficulty of assigning a limit to the depth of the enriched zone, which, for practical purposes, is determined by the percentage of copper, not by the incipient formation of chalcocite.

The general conclusions of this examination of the ores are as follows:

1. The copper occurs as a definite mineral in the ore, and not chemically combined with the pyrite. This agrees with the conclusion of James F. Simpson on the copper of the lean ore of Butte, Mont.[1]

2. The order of deposition of the primary minerals has been: pyrite, chalcopyrite, blende, galena.

3. The processes of secondary enrichment consist, in lean deep ores, chiefly in a change from chalcopyrite to chalcocite; and in richer or shallower ores, chiefly in deposition of secondary chalcopyrite, followed by chalcocite.

4. The preliminary changes due to enrichment extend far down into what is usually regarded as primary ore.

5. Finally, it must be emphasized that in these ores the primary copper mineral is chalcopyrite, chalcocite being the result, so far as the writer has observed, of alteration by descending solutions only. The statement of Charles H. Jones, that the copper in the Spanish pyrite occurs as chalcocite[2] can only be partially accepted. Chalcocite is certainly common in many ores, but it is not the primary mineral. The conclusion only serves to emphasize the great extent to which secondary alteration has proceeded in these lodes.

[1] "The Relations of Copper to Pyrite in the Lean Copper Ores of Butte, Montana," ECON. GEOL., III., 1908, p. 628.

[2] "Wet Methods of Extracting Copper at Rio Tinto," *Trans. Amer. Inst. Min. Eng.*, XXXV., 1904, p. 3.

DESCRIPTION OF TYPICAL MINES.

It will be of interest here to summarize the chief features of some type deposits, which were specially examined during the present work. Of these, Rio Tinto has been described by earlier writers, but subsequent developments have disclosed important facts as to the relations and the ore content of the lodes. Sotiel and Santa Rosa, two of the mines belonging to the United Alkali Company, of Liverpool, are types of lodes enclosed in slate, and showing some interesting structural features.

Rio Tinto.—The geology of this district is indicated on the accompanying map and section (Figs. 40 and 41 following). There are two parallel belts of rhyolite-porphyry, highly crushed and sheared, especially along their margins, and surrounded by phyllites and slates. A parallel sill of diabase, with some phases of coarser augite-diorite, occurs further south. The first porphyry belt carries the northern group of lodes on one flank, and the San Dionisio and South Lodes on the other, while the Valley lode, at Bella Vista, lies at the junction between the slates and the second porphyry belt.

The lodes are composed, in all cases of massive pyrite, often faintly banded, and with subordinate quantities of highly banded ore. The walls are generally well defined, and occasional horses of country rock—both slate and porphyry—are enclosed in the lodes. Brecciated porphyry is frequently seen along the walls of some of the lodes, the rock fragments being cemented by quartz and seams of pyrite. All the outcrops are marked by prominent ironstone gossan, which extends to a depth of from 25 to 35 meters.

The northern group of lodes are enclosed in the porphyry, close to its junction with the slates, although slates sometimes appear against the ore. The lodes are contained in a complex zone of shearing and faulting, and practically constitute one great replacement lode, although as workable ore bodies they are separated by intervals of porphyry. The north lode has a length of 450 meters and a maximum width of 180 meters. El Lago is a smaller adjacent mass, measuring 300 by 75 meters. La Dehesa lode has a total length of over 700 meters. A feature

of all the masses is their rounded outline and the comparatively shallow depth to which they extend, namely, 100 meters. At the bottom, they close in abruptly, with flat bases. This is in marked contrast to the tapering terminations of lodes in slate. The ore of the three lodes has been much leached by descending

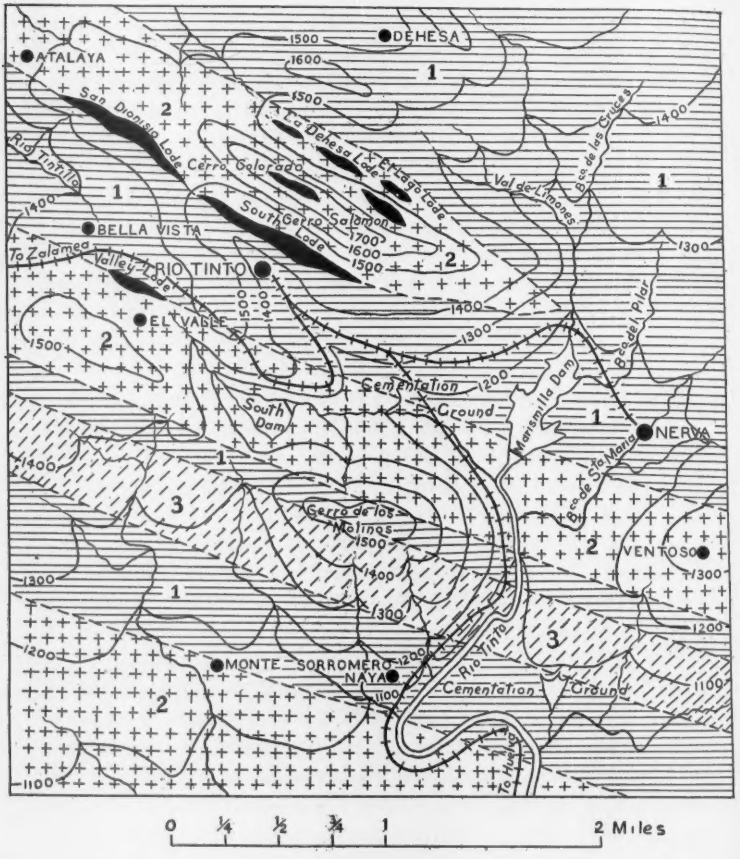


FIG. 40. Geological map of Rio Tinto. Contour interval 100 ft. 1, slates (culm); 2, porphyry; 3, diabase.

waters, and often impoverished, while they are traversed by veins and strings of secondary sulphides in joints and cracks of the ore, as well as in the adjacent country rock. Secondary enrichment has thus been effective right to the bases of these lodes.

A gossan outcrop occurs on the porphyry ridge of the Cerro Salomon. It was explored by a shaft to a depth of about 30 meters, carrying porphyry on both walls. It has apparently not been ascertained, however, whether it is succeeded by any quantity of sulphide ore, or whether it is merely the oxidized root of a denuded lode.

San Dionisio and the south lode are each about 1,000 meters in length, and occur on the same line of strike, being practically connected by small seams and bunches of ore. At the surface, they lie between porphyry and slate. In depth, however, the slate on the south wall is replaced by porphyry, which thus completely encloses these lodes. This porphyry is petrographically

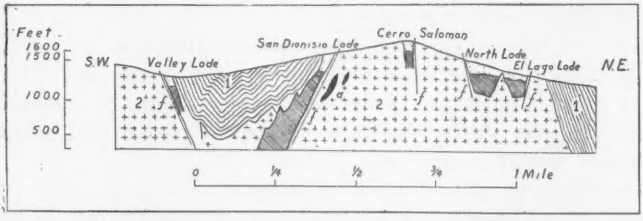


FIG. 41. Generalized section across the lodes of Rio Tinto. 1, slates (culm); 2, porphyry; *a*, masses of secondary chalcocite; *f.f*, faults or shear zones.

identical with that on the footwall and also with that which outcrops at Bella Vista. It appears, therefore, that the separated outcrops are both branches of a single mass, the intervening belt of crushed and contorted slates having been either caught up between the two branching portions of a single intrusion, or subsequently involved by faulting. The Valley lode, lying between this slate and the porphyry at Bella Vista, appears, as indicated in the section, to stand in the relation of a hanging

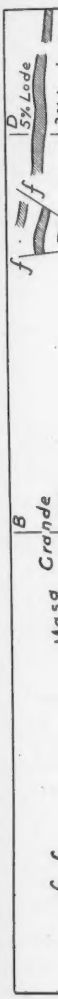
wall branch to San Dionisio. There is no doubt, from the structure of this part of the section, that intense shearing has taken place along the two flanks of this belt of slate, where it adjoins the two masses of porphyry.

The South lode has a maximum width, near its east end, of 160 meters, and in depth it closes in rather rapidly in most places. San Dionisio has attained a maximum width of 250 meters, where the slate gives place to the porphyry on the hanging wall. It is being worked to the depth—exceptional on this field—of nearly 500 meters, and has been proved a considerable amount deeper. The enriched zone of this lode extends to a depth of about 150 meters, though, as already mentioned, secondary processes commence much deeper in places. A noteworthy feature of San Dionisio has been the occurrence of large masses of secondary ore—chiefly chalcocite—in the porphyry some distance from the foot wall of the lodge (Fig. 41, *a*). This ore averaged from 8 to 10 per cent. of copper, and was found to a depth of over 100 meters. In the lowest levels, the value of the ore falls to about .8 per cent.

Of the lodes at Rio Tinto, the northern groups are approaching exhaustion, and the available ore for the future is chiefly in the great San Dionisio lode. The reserves were estimated in 1906 at over 130 million tons, or about 70 years' life at the present rate of production.

Sotiel (Fig. 42).—The lodes of this mine follow a distinct zone of shearing in the sedimentaries, parallel to and a little to the north of a belt of highly sheared porphyry. The enclosing slates have been converted into sericite- and chlorite-schists. The total length of the lode-zone is over 1,000 meters, and the general inclination of the members is to the north.

The chief ore body of the group is the Masa Grande, over 600 meters in length of outcrops. At its west end it divides into small branches which have been much distrubed by faulting. The main mass of the lode, to the east, is also divided up into "legs" by intervening wedges of slate, and a conspicuous "horse" occurs in the center of the lode. At the adit-level (150 meters) it rolls over with a flexure in the slates and has a flat



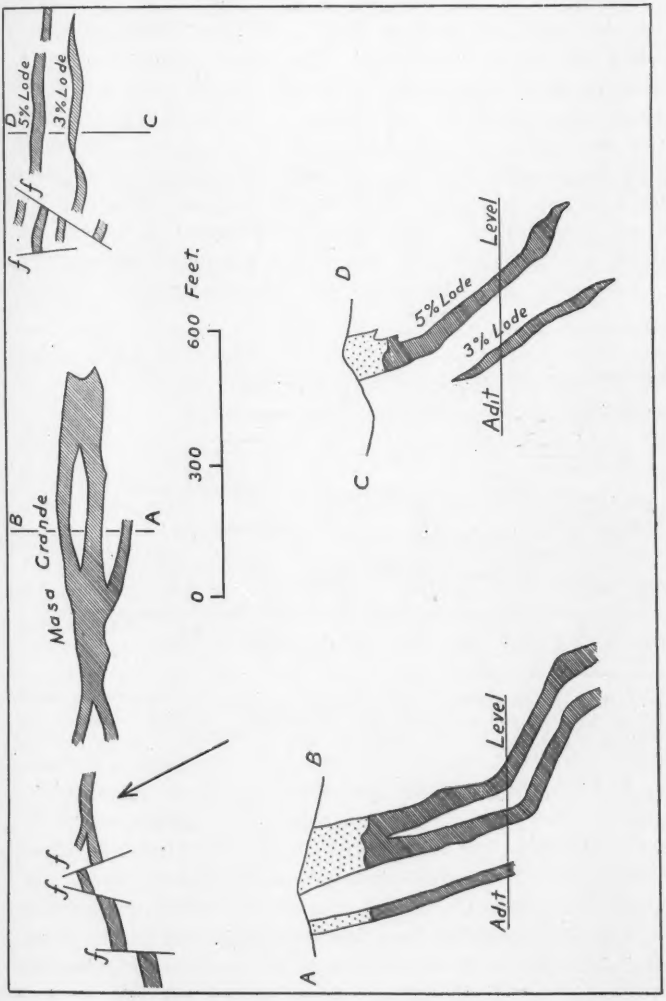


FIG. 42. Plan (on adit level) and cross sections of Sotiel lodes. *f f*, faults.

dip down to 200 meters, when it again bends over, still following the slates, and becomes steep. The lode walls are everywhere smooth and well defined. The ore is a fine-grained pyrite, generally more or less banded parallel to the walls, and sometimes conspicuously so. It often carries a good deal of blende, the average zinc content being 3 to 5 per cent. The copper content gradually decreases in depth, but above the adit level much of the ore has been enriched, assaying as a rule from 3 to 5 per cent. or more. At a depth of 200 meters, at the east end of the lode, a fault occurs, along which a seam of secondary ore (chalcopyrite and chalcocite) has been deposited. This is

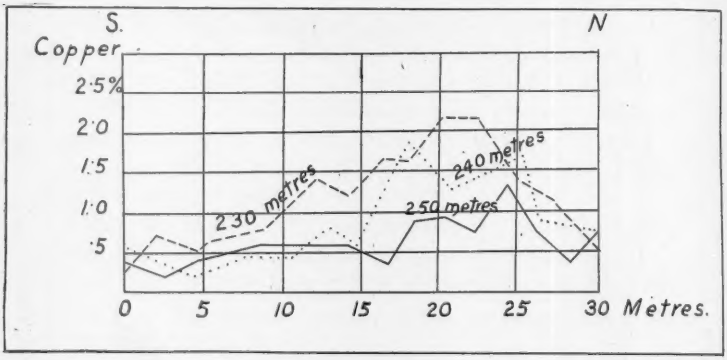


FIG. 43. Curves of assay values on cross section of Masa Grande, Sotiel, on the 230-, 240- and 250-meter levels respectively. Showing ore shoot near north wall and decrease of copper in depth.

another instance of the depth to which secondary processes have been effective under favorable circumstances, as the ore of the lode at this point is a lean pyrite. A feature of this lode, which was found also in some others where assay plans were available, is the superposition of corresponding values at successive per cent. in places, has been followed down to a depth of 200 vertical levels, which is illustrated in the accompanying diagram (Fig. 43). A distinct shoot of ore, indeed, assaying up to 3 per cent., in places, has been followed down to a depth of 200 meters, lying near the hanging wall. In cross-section it shades

off gradually into lean ore on the walls, assaying 1 per cent. or less. This was the most conspicuous localization of ore which was observed during the present work.

East of the Masa Grande there are several smaller lodes, in places much confused by faulting. The two most important are the "Three-per-cent." and the "Five-per-cent." lodes.

The "Three-per-cent." lode does not outcrop, but feathers out 90 meters below the surface. When followed down, it continues, dipping to the north at 60°, for a further depth of 80 meters, where it again wedges out. As it goes down, it also shortens, from a length of 100 meters, towards a point. Its mean width is 3 to 4 meters. The ore is conspicuously banded, and crowded with inclusions of slate. Brecciated slate cemented by compact ore also occurs. The lode has clearly been formed by the partial replacement of a belt of highly crushed slates. Owing to the absence of an outcrop, secondary enrichment has not affected the ore to any extent. The average copper content of the lode is very nearly 3 per cent., but the richest ore occurs here also in a central shoot which carried 3.5 or 4 per cent. in the upper levels, falling to 1.5 or 2 per cent. in depth. Chalcopyrite frequently occurs in blebs and strings in the more slatey portions of the ore. The zinc-content sometimes reaches 10 per cent., but the average is about 3 per cent., with 1.5 per cent. of lead.

The "Five-per-cent." lode is a zone of mineralized schist, extending from the surface to a depth of 140 meters, when it gradually fades out. Like the last, it also shortens in depth.

It lies 40 meters north of and parallel to the "Three-per-cent.," and has a mean width of 20 meters, but widens considerably near its lower end. The walls are fairly defined, and the enclosed contorted schist carries about 1 per cent. of copper over all. "Horses" of poorly mineralized schist occur within the zone, as well as seams of massive ore, in which all trace of the original rock structures is lost. These are frequently rich, assaying up to 5 per cent. of copper. Rich patches of ore (6 per cent.) were also encountered near the bottom of the lode; these were almost certainly of primary origin. The gossan is marked

by a zone of ferruginous slates, in contrast to the ironstone gossan of the typical massive ore.

These two lodes show to great advantage the different stages of formation of the ore by replacement, and give much valuable evidence on this question.

Santa Rosa.—There are three, and possibly more, lodes in this mine, enclosed in slate, and of the typical lensoid form. Their features are well illustrated in El Tinto lode (Santa Rosa, No. 1) (Fig. 44). This strikes N. 60° W., and dips to the

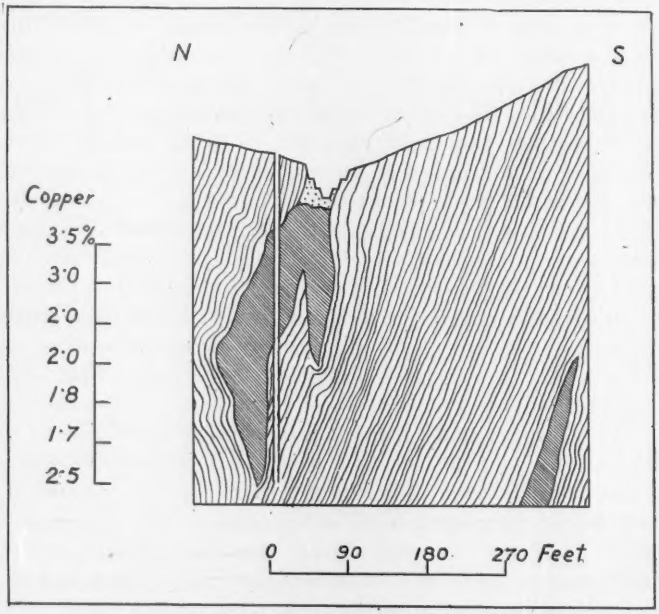


FIG. 44. Vertical section of El Tinto, Santa Rosa.

north at an angle of 75° or more. The foot wall is even, but the hanging wall shows frequent rolls, with contortion of the slate, the bedding of which is sometimes cut by this wall of the lode. It is wedge-shaped in plan, the east end tapering off gradually, while west end is blunt, tongues of slate running into this end

in places. A footwall spur or leg also occurs, as shown in the accompanying cross-section. The length of the lode at its outcrop is 400 meters, and its greatest width is 30 meters. In depth it shortens rapidly, closing in to 70 meters at a depth of 110 meters, and finally tapering out 130 meters below the surface. These features are illustrated in the longitudinal section (Fig. 45). The ore is slightly banded, and practically free from country rock. The depth of gossan is from 15 to 25 meters.

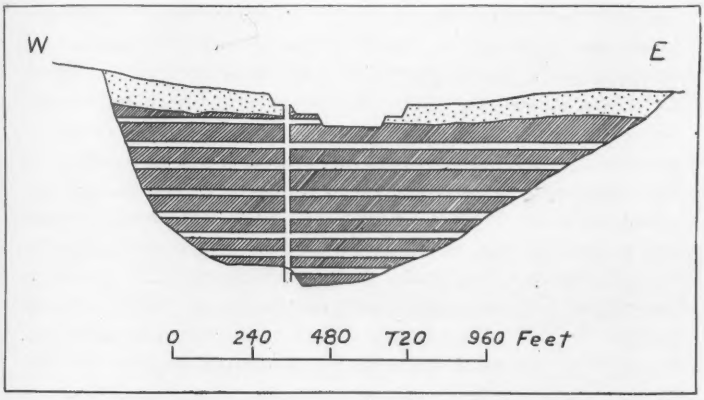


FIG. 45. Longitudinal section of El Tinto lode, Santa Rosa.

The enriched ore beneath averaged 3 to 4 per cent. of copper, gradually decreasing in depth (Fig. 44). At the bottom of the lode, however, strings of primary chalcopyrite occur in the ore and in the adjoining slate. In this lode, as in the Masa Grande, variations in value along any one level are repeated in the successive lower levels.

San Cornelio lode is a similar lens, lying 150 meters to the south of El Tinto, and shown in the cross-section. It does not outcrop, its highest point being 150 meters below the surface. Only its upper part has as yet been exposed.

GENESIS OF THE DEPOSITS.

Views of Previous Writers.—The origin of these and similar ore bodies has been a much-discussed problem in ore genesis. The earlier workers, notably F. Römer (1873–76), regarded them as of sedimentary origin, contemporaneous with the enclosing rocks. J. H. Collins (1885) believed that the lodes were formed along lines of fissuring, the ores being derived from the country rock by lateral secretion. Gonzalo y Tarin (1888) and De Launay (1889) held that they were essentially vein deposits from ascending solutions. F. Klockmann (1894) revived the sedimentation hypothesis, and maintained also that the porphyries were contemporaneous lavas and tuffs. These views are still supported by Alfred Bergeat for many pyritic deposits.[1] In 1899, J. H. L. Vogt concluded that the lodes were essentially pneumatolytic in nature and a direct after effect of the intrusion of the porphyries, to which they bore an intimate genetic relation. In 1902 Klockmann, after a further examination of the deposits, maintained that they were "concretionary segregations in a plastic clay mud, impregnated with the chemical elements of the pyrites," by the porphyry "lavas," which he regarded as the "ore-bringers." He also traced a connection between the pyritic lodes and the blackband iron-stones and sphæro-siderite of the coal measures. In 1905, J. W. Gregory reviewed the evidence, and inclined to the view that the Spanish deposits had been formed by replacement along great fault plans.[2] Finally, Bruno Twetzig, in 1906, supported the syngenetic view.

Criticism.—Many facts are directly opposed to the sedimentation hypothesis, and at the same time strongly support the view that the lodes are epigenetic. The chief arguments are: That the lode walls sometimes cut the bedding of the slates, though this is not admitted by Professor Klockmann; that the porphyries are (believed to be) later intrusives, and hence lodes en-

[1] A. W. Stetzner and Alfred Bergeat, "Die Erzlagerstätten," Leipsig, 1906, pp. 357–361.

[2] J. W. Gregory, "The Mount Lyell Mining Field, with some Account of the Geology of other Pyritic Ore Bodies," *Trans. Austr. Inst. Min. Eng.*, X., 1905, p. 165.

closed wholly or partly in these can scarcely have been contemporaneous with the slates; the occurrence of ore shoots; the thermal alteration of the enclosing rocks; the paragenesis of the sulphides; the lack of persistence of the lodes; and the occurrence of stringers and branches running out into the country-rock. These facts cannot be satisfactorily explained on the sedimentation hypothesis.

Klockmann's modified theory is somewhat vague, and is further connected with his view as to the effusive nature of the porphyries. The available evidence all goes to indicate that the ores are much younger than the porphyries, and the occurrence of lodes in slate some distance from porphyries, is also opposed to this view.

The original lateral secretion hypothesis is quite inadequate to explain the origin of the lodes, nor is there any evidence to indicate that the ores were first brought up by the porphyries and subsequently concentrated in the fault zones.

Vogt's hypothesis presupposes a close genetic relation between lodes and porphyries. This, however, is doubtful. The intrusion of the porphyries was followed, as already explained, by intense earth-pressure and movement, then by basic intrusions, and then by the formation of great shear-zones. Not till after this last disturbance is there any evidence of the appearance of the ores. The association of the lodes with porphyries is not by any means the general rule, although, owing to the great profusion of these rocks, lodes are seldom found at a great distance from them. In many cases, however, diabase sills are found close to the lodes, and sometimes along one wall, instead of the older porphyries. Thus Fritschi y Fitz has referred the lodes of Castillo de las Guardas to thermal after-effects of the associated diabase intrusions.[1]

Results of the Present Work.—The writer's conclusions are essentially in agreement with the suggestion of J. W. Gregory, namely, deposition by replacement in zones of faulting or shearing. The order of events during the Hercynian epoch was:

1. Folding and intrusion of porphyries and granitic rocks,

[1] "Las Minas de Castillo de las Guardas," *Revista Minera*, 43, 1892, p. 58.

followed by further pressure, with crushing and shearing of the porphyries.

2. Intrusion of basic dykes and sills.

3. Development of thrust planes along lines of weakness, as an effect of further earth-pressure.

4. Formation of the lodes, the ores being transported by ascending thermal solutions, and deposited, as already explained, by replacement of the zones of crushed rock in the thrust planes.

The place relation of the lodes to the exposed igneous rocks, more especially to the porphyries, is believed to be structural rather than genetic. At the same time, the ore deposition is regarded broadly as an after effect of the whole series of igneous intrusions; and the emphasis laid by Vogt on the relations between pyritic masses and igneous processes in general, is strongly supported in this district. There was probably a close genetic relation between the pyritic ores, and the original Hercynian magma from which the whole series of igneous rocks was differentiated. The occurrence of the lodes throughout a circumscribed area, and the fact that the peculiar development of igneous rocks described, is also confined to practically the same area, certainly indicates that the origin of the ores has been closely involved with the subcrustal processes of earth movement, and the attendant magma differentiation. It is, indeed, difficult to account for such masses of compact sulphides without assuming a previous concentration by border segregation in deep-seated igneous rocks, prior to the ascent of the thermal ore-bearing solutions. To such a process seems to be due the restriction of the pyritic deposits to a confined petrographic province, while normal quartz-veins, carrying copper and other ores, are found all over the south of the peninsula, unaccompanied by a defined series of igneous rocks. This pyritic zone is, indeed, a very fine example of a metallogenetic province in intimate relation with a corresponding petrographic province.

While, therefore, a considerable time interval separated the ore deposition from the earlier intrusion of the porphyries, the writer is strongly of opinion that the ores are a result, in the first place, of processes of differentiation and segregation accom-

panying the earth movement and igneous intrusions over the restricted area where the lodes occur. The ores, in short, are believed to be the end product of the magmatic differentiation to which the series of igneous rocks in this district has been due.

It is significant that pyritic deposits in general show all the gradations through the successive genetic types of ore deposits, that are to be found in normal veins. Thus some are practically magmatic segregations, some are closely allied mineralogically to the generally understood contact type, others are accompanied by pneumatolytic products or are associated with pegmatites, and there then follow the normal vein types, carrying one or more of the common sulphides. There seems therefore strong evidence for regarding the pyritic deposits as specialized types of normal vein-deposits; the specialization being due, in part to magmatic processes, and in part to local factors which must be determined in each case.

A difficult problem is the exact significance of pyrrhotite and magnetite in association with the pyrite, as, for example, in the Cala deposits of Huelva, and in many other important districts. Professor Klockmann regards the development of pyrrhotite[1] and magnetite as an index of the amount of metamorphism, whether thermal or dynamic, that the original pyrite has undergone, and there is no doubt that metamorphic processes have played an important part in modifying pyritic deposits in some districts. A recent investigation of the pyritic deposits of the Appalachian belt by W. H. Emmons[2] emphasizes this; while metamorphism is upheld by Otto Mann[3] in regard to the Segen Gottes deposit of the western Erzgebirge. In many pyritic fields, however, subsequent metamorphic processes have played a minor part, and this is believed to be true of the Huelva district. In such cases,

[1] F. Klockmann, "Ueber den einfluss der metamorphose auf die mineralische zusammensetzung der Kieslagerstätten," *Zeits. für prakt. Geol.*, XII., 1904, p. 153; "Ueber Kontact-metamorphose magnetitlagerstätten, ihre bildung und systematische stellung," *ib.*, p. 73.

[2] W. H. Emmons, "Some regionally metamorphosed ore-deposits, and the so-called segregated veins," ECON. GEOL., IV., 1909, p. 755.

[3] Otto Mann, "Zur Kenntniss die Kieslagerstätten im Westlichen Erzgebirge," *Abhandlungen der Naturwissenschaftlichen gesellschaft Isis in Dresden*, 1905, p. 86.

the relative proportion of pyrrhotite and magnetite would seem to be an index of the physical conditions, *i. e.*, pressure and temperature, under which the ores were deposited.[1]

In this connection it is noteworthy that these two minerals occur frequently, as at Cala, in those pyritic deposits which are of the contact type, strictly speaking, or which are closely connected with deep-seated igneous masses; while these minerals become less abundant or disappear, in deposits more remote from their igneous source. Magnetite and pyrrhotite, in other words, seem often to indicate deposits of the deep zone. As in most cases, such deposits are later than or contemporaneous with the associated plutonic masses, the development of these minerals cannot then have been due to the effects of the intrusion or of accompanying earth movements on a previously existing ore body.

Conclusions.—The general conclusions of the present investigation are briefly as follows:

1. The pyritic ore bodies of the Huelva district constitute a metallogenetic province accompanying a petrographic province, and the concentration of the ores has been due, in the first place, to a process of magmatic segregation of sulphides accompanying the differentiation of the igneous rocks, and dependent, with this latter, on the Hercynian tectonic movements.

2. The ores have been deposited from solutions which, after the cessation of the igneous outbursts, rose along great thrust planes or shear zones, and the deposit was effected by replacement of the sheared and crushed rock by the ores.

3. Since the fromation of the lodes, great denudation, with accompanying sulphide enrichment (by descending waters) has taken place, and to this enrichment the economic importance of the deposits as a source of copper, and the leading position of this field among the great copper districts, is very largely, if not entirely, due.

[1] Waldemar Lindgren, "The Relation of Ore-deposits to Physical Conditions," ECON. GEOL., II., 1907, p. 105.

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GEOLOGY AND ORE-DEPOSITS OF THE GOLDFIELD DISTRICT, NEVADA.[1]

F. L. Ransome.

Part II. Mines and Mining.[2]

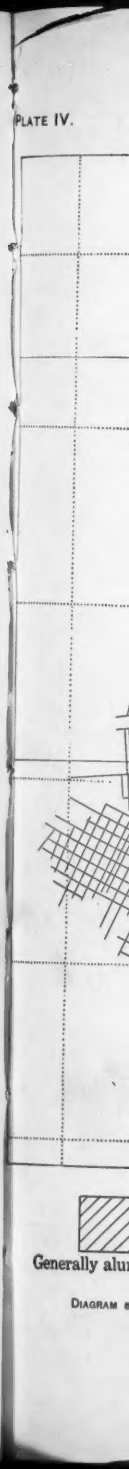
The principal mines of the Goldfield district fall into two areal divisions, which may be conveniently designated the "Goldfield" and "Diamondfield" groups. Of these the first has supplied over 95 per cent. of the output of the district and includes such well-known mines as the Mohawk, Combination, Florence, Jumbo, January, Red Top and Sandstorm.

The belt of productive mines of the Goldfield group sweeps from Kendall Mountain on the north in a gentle curve, concave to the northeast, past Columbia Mountain and Milltown, to a point about half a mile southeast of the latter settlement. It may be subdivided into a group of mines on the north, including the Sandstorm, Kendall and Conqueror, which are in rhyolite; a very important group northeast of Goldfield, which is mainly in dacite, although latite is found in the deeper levels, and includes the Red Top, Mohawk, Combination, January and Jumbo mines of the Goldfield Consolidated Mines Company, the Combination Fraction mine, and part of the Florence mine; and, finally, some mines, principally lessee workings, east of Goldfield, in the Milltown andesite.

The mines of the Diamondfield group are aligned along McMahon Ridge north of the town, and stretch from Black Butte

[1] The Goldfield district has been fully described in Professional Paper No. 66 of the U. S. Geol. Survey. The present paper is an attempt to present the salient results of that investigation in as concise a form as is possible and was prepared at the suggestion of the editor. The reader desiring fuller information regarding any phase of the subject here briefly treated is urged to consult the original report.—F.L.R.

[2] Part I of this paper appeared in Volume V., No. 4, of this Journal, pp. 301–311.



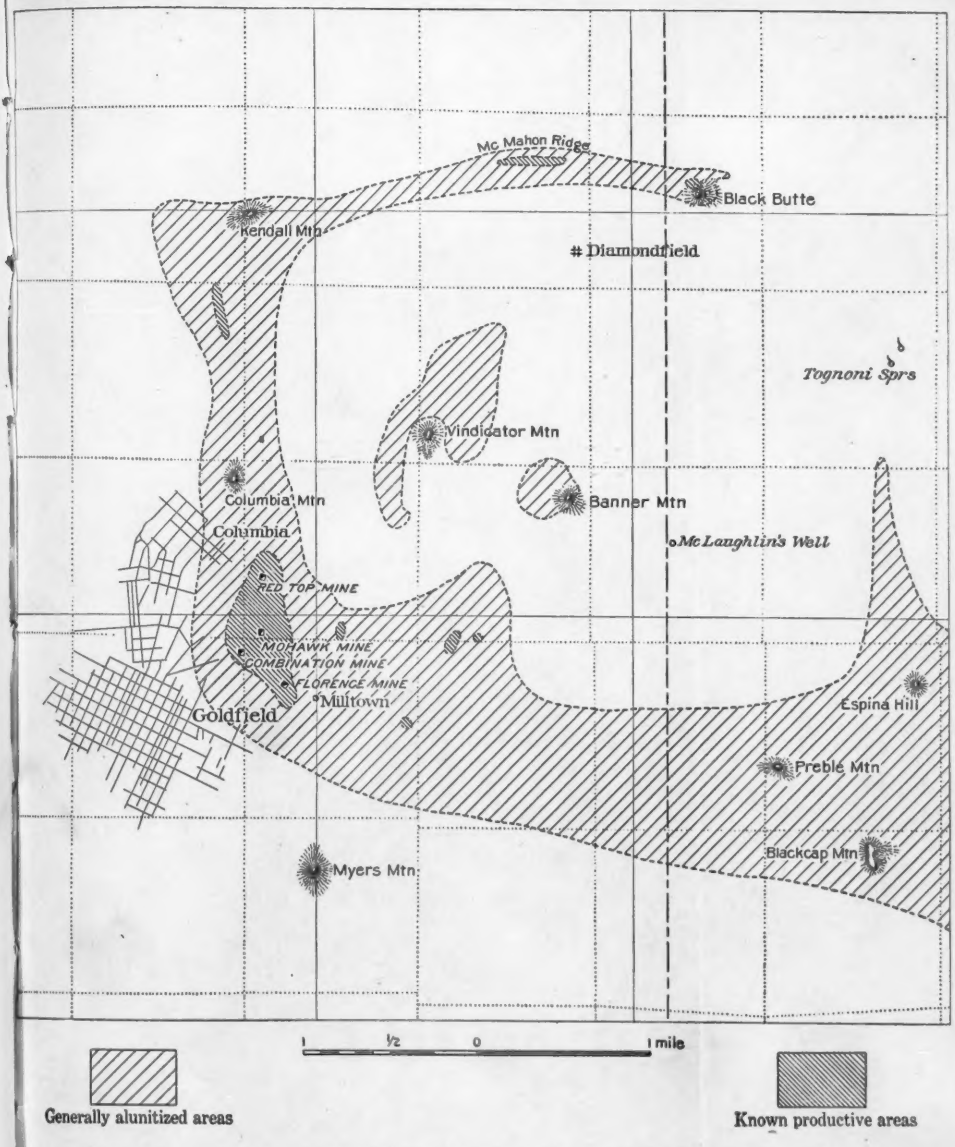


DIAGRAM SHOWING THE PORTIONS OF THE GOLDFIELD DISTRICT IN WHICH THE ROCKS HAVE UNDERGONE EXTENSIVE ALUNITIC ALTERATION.

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on the east for a distance of about a mile to the west. These are mainly in the Milltown andesite.

A general idea of the distribution of the mines may be had from Plate IV., intended primarily to show the areas especially affected by alunitic alteration.

By far the most important aggregation of mines under one ownership is that of the Goldfield Consolidated Mines Company. The connected underground workings of this property, now the most productive gold mine in the world, extend from north to south a distance of nearly 4,000 feet, have a maximum width of over 2,000 feet and attain a depth of about 1,000 feet in the vicinity of the Clermont shaft.

Although milling began at the Combination mine in 1904, the year following the opening of the district, a large part of the rich ore for which Goldfield has become famous was mined by lessees and shipped crude, some carload lots averaging over 600 ounces of gold to the ton. By the end of 1908 the Goldfield Consolidated Mines Company had completed its 100-stamp mill and thereby opened a new era in ore treatment. According to its last report, this company during the fiscal year 1908–9 produced ore of the gross value of $6,832,652, averaging $37.98 a ton. The average assay value of the mill-ore was $33.45 a ton, of which 94.49 per cent. was recovered at a milling cost of $1.951 a ton. The total cost of mining and milling averaged $6.77 a ton. The average value of ore from the Florence mine in 1909 is given as $19.75 a ton, with a total mining and milling cost of $12.49 a ton.

The gross production of the Goldfield district from the beginning of mining to the end of 1908 is shown in the following table, the figures being taken from the reports on the production of gold and silver published by the United States Geological Survey. The silver is calculated at the average commercial value at New York for each year. As the figures represent gross output, no deductions have been made for freight, treatment or loss in smelting.

PRODUCTION OF THE GOLDFIELD DISTRICT.

Year.	Ore.	Gold.		Silver.		Total Value.	Average Value per Ton.
		Quantity.	Value.	Quantity.	Value.		
	Short tons	Fine ounces		Fine ounces			
1903	335	3,418.66	$70,670	287	$155	$70,825	$211.41
1904	7,433	113,293.23	2,341,979	19,954	11,374	2,353,353	316.60
1905	19,548	91,087.76	1,882,951	8,589	5,188	1,888,139	96.58
1906	59,628	339,890.20	7,026,154	15,648	10,484	7,036,638	118.00
1907	101,136	406,756.16	8,408,396	71,710	47,329	8,455,725	83.61
1908	88,152	236,082.14	4,880,151	30,823	16,336	4,896,587	55.55
	276,232	1,190,528.15	$24,610,401	147,011	$90,866	$24,701,267	

There was produced also, in 1908, 1,606 pounds of copper, valued at $212. Statistics for 1909 are not available at the date of writing but the total value of the output for that year is probably in the neighborhood of $11,000,000.

Electricity generated at Bishop, Cal., is the principal power used for mining and milling.

THE LEDGES.

The Goldfield deposits, in all that pertains to the genesis of the ore, are most closely allied to metasomatic fissure veins; yet they can scarcely be included within that class. They are intimately related to fissuring; but only a small part of the ore has actually filled fractures. These fractures, moreover, rarely show that regularity in form and that persistency in strike and depth which are connoted with the term "vein" or "vein fissure." Structurally the deposits are irregular masses of altered and mineralized rock traversed by multitudes of small, irregularly intersecting fractures, such fracturing passing in many places into thorough brecciation. Certain exceptional deposits exhibit in part more regularity of form and there is reason to suppose that at depths greater than those now reached such approaches to lode-like form may become more numerous.[1] But within the mass of rock extending from the surface to a depth of 1,000 feet, a mass which includes all the ore bodies thus far exploited, the deposits can not be called lodes or veins without giving to these words unusual meanings or without tacitly ascrib-

[1] This suggestion is apparently confirmed by the latest reports from the district. F. L. R.

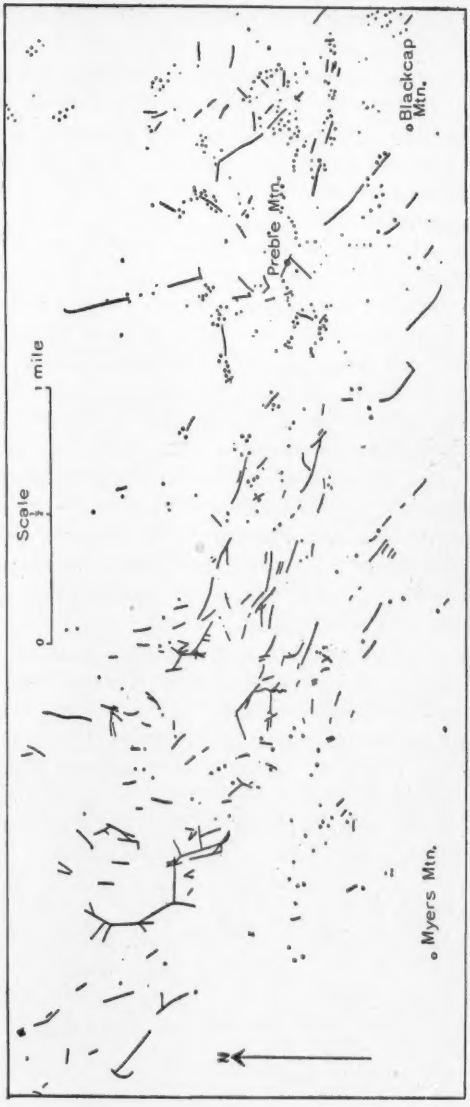


FIG. 46. Plan showing distribution of ledges east of Goldfield.

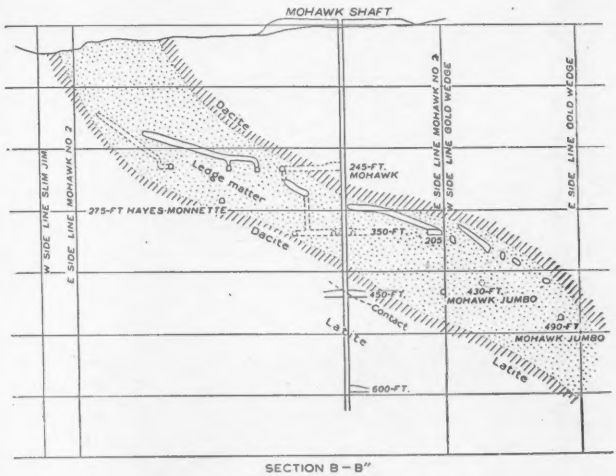
ing to the mineralized bodies a tabular form that they rarely possess.

In view of these considerations, the word "ledge," already in use by miners in a less definite sense than "vein," has been employed to designate the masses of silicified or otherwise altered rock in which the ore bodies are found. The actual ore bodies or pay shoots occur within, but are seldom coextensive with the ledges or ledge matter.

The ledges, considered as topographic features and independently of ore bodies, are extraordinarily abundant in the Goldfield district. To them the topography owes most of its minor roughness; many small knobs are crowned with iron-stained masses of ledge matter and the slopes of the larger hills are ridged and studded with the same material. As stated on page 301, these rough outcrops are in most, if not all, cases purely residual, and stand out, like pebbles in a clay bank, because the softer rock has been eroded from around them. Many of them in fact rest like giant pebbles on the tops of knobs and have no downward continuation into the soft rock beneath them. In general the distribution of the ledges is indicated by the areas of alunitization shown in Plate IV. They are especially abundant east of Goldfield as may be seen from Fig. 46.

The most of the ledges are irregular masses of no definite trend. Others, of which the proportion appears magnified by the method of representation adopted in Fig. 5, have linear outcrops and are evidently related to fissures or fissure zones of some persistency, attaining in extreme cases a length of a quarter of a mile. These exhibit great diversity of direction and in some parts of the field, particularly near Milltown, ledges of various trends are linked together in complex chains. Most of the productive ledges near Goldfield have a north to northwest strike. Although diversity of strike is one of the most conspicuous features of the ledges as a whole, there is some approach to uniformity in the tendency of the longer ledges to conform in direction to the general trend of the belt in which they lie. The linear ledges are in most cases straight or but slightly curved. Others, such as the January and Florence ledges, are sharply bent, as may be seen from Plate V.

A large number, probably most of the ledges, have nearly vertical dips. Others, such as the mass of ledge matter capping Black Butte, and the so-called Flat vein in the same hill, are nearly horizontal. The Mohawk ledge as a whole (see Fig. 47) has a dip of 35° to 45° to the east. The Combination ledge (see Figs. 8 and 9), while very irregular, also dips to the east,



SECTION B—B″

FIG. 47. Section across the Mohawk ledge.

the angle of dip becoming very low on the deeper levels. Most of the ledges that have been followed down for a few hundred feet show changes in dip such as are rarely found in typical veins or lodes. These changes are well illustrated in the January, Combination, Reilly and Florence workings.

The shape of the ledges has been partly indicated in the preceding description. It has been shown that they range from roughly equidimensional, irregular masses to nearly vertical or inclined, undulating, lodelike plates or sheets. As examples of fairly regular, lodelike ledges may be cited parts of the main ledge of the Combination mine, the Jumbo ledge and the Little Florence ledge. The Mohawk ledge as a whole is generally lode-

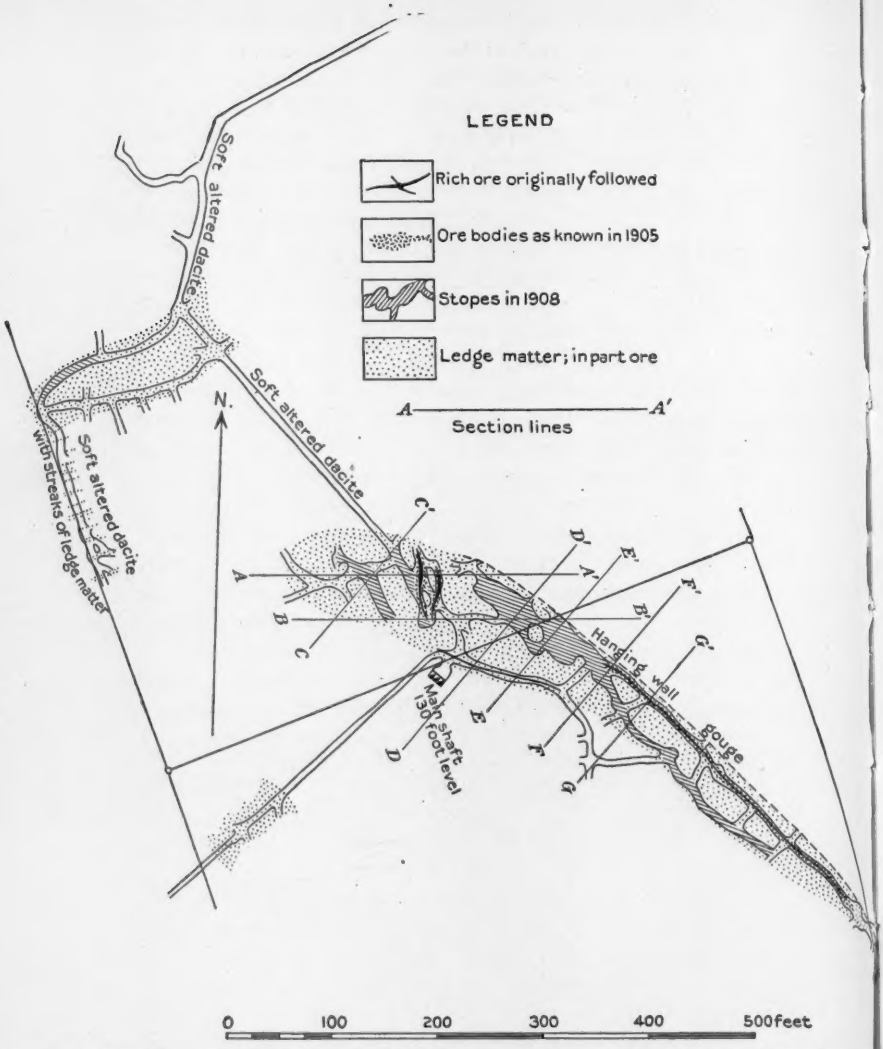


FIG. 48. Plan of the 130 ft. level of the Combination mine, showing relations of ore ledge-matter and

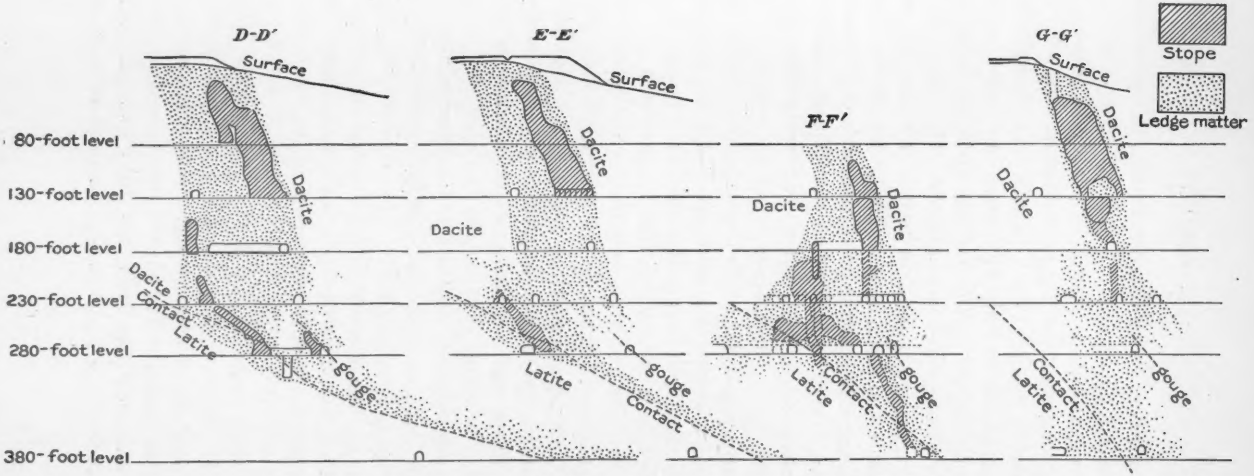


FIG. 49. Sections across the Combination ledge. Same scale as Fig. 48.

like, but is a very broad ill-defined mass, whose boundaries are as yet imperfectly known. Regularity observable on a given level is no guaranty of vertical regularity or persistence, as is shown by the sections of the Combination mine (Fig. 49) and by the changes in dip of the Combination and Reilly ledges.

As the upper parts of the most important ledges are in dacite, the material of those in this rock appropriately received the first attention. Within the zone of oxidation, the typical dacitic ledge matter is a rusty, shattered or brecciated mass that commonly contains, here and there, bunches and streaks of kaolinite, which may be mixed with limonite or alunite, or both. The fragments of the breccia may be loose, with considerable interstitial limonitic or kaolinitic material, or may be cemented by quartz, limonite or hematite. The fragments of the breccias vary much in size, and it is impossible to draw any definite line between brecciation and close irregular fissuring. In many places the rock appears to have been shattered without any noticeable displacement, rounding or trituration of the fragments.

The ledge matter as a whole is porous and permits the downward percolation of atmospheric water, while the soft pyritized dacite on both sides is relatively impervious. Hence, oxidation extends much deeper in the ledges than in the adjoining country rock and gives rise to a sharp color-distinction between rusty ledge matter and gray pyritized dacite.

The fragments in the oxidized ledge matter, which were originally dacite, are usually stained with iron oxide and now consist of gray, flinty, aphanitic quartz with a porous texture. Close inspection of this material shows occasional phenocrysts of quartz which have persisted practically unchanged while other minerals have altered to secondary aggregates around them. The pores are spaces once filled by feldspar and by ferromagnesian minerals in the original dacite. These minerals were first changed, during ore deposition, into aggregates consisting chiefly of alunite and pyrite, respectively. Later, during the progress of oxidation, the pyrite and alunite were removed and the spaces they once occupied were lined with drusy films of quartz. The removal, however, is complete only near the surface. In much

of the rusty ledge matter the fragments, when freshly broken, show pyrite and alunite. Not all of the pyrite and alunite are distinctly pseudomorphous, but these minerals are in part disseminated in minute crystals through what was once the groundmass of the dacite.

Below the limit of oxidation the ledge matter is usually less siliceous, less porous, and of course is not discolored by oxides of iron. The many small fissures and interstices in the mass are commonly filled with a soft white substance which is usually alunite or a mixture of alunite and kaolinite. The material of the fragments, or between the fissures, shows more clearly than in the oxidized zone that it is altered dacite, the feldspar phenocrysts being represented by aggregates of alunite instead of by quartz-lined cavities.

In some ledges and parts of ledges there is no evidence of more than one period of fissuring and mineralization; others have had a more complex history and contain fragments which show signs of an earlier fissuring and silicification. In the latter case, the ore is associated with the younger disturbance. Some ledges, also, have undergone some fissuring after the primary ore deposition, as will be shown in subsequent pages.

Ledges in andesite have not been so fully explored as those in dacite, but they exhibit similar structural features. They are exemplified by the ledges worked in the Engineers', Little Florence and Rogers leases in Florence Hill. The discovery of these ore bodies from 1906 to 1908 shows that andesitic ledges may contain ore fully as rich as those in dacite. Recent deep development below the dacite in the Clermont workings and elsewhere has shown also that some of the largest and richest ledges continue downward with no essential change of character into the latite.

The only rhyolitic ledge in which extensive work has been done is that of the Sandstorm and Kendall mines. Within the oxidized zone, the fissured rhyolite is thoroughly silicified and the walls of fissures and the surfaces of fragments are often encrusted with barite. The interstices are filled with kaolinite, usually more or less rusty and containing in many places crystals

of barite. Below the zone of oxidation there is little to distinguish ledge material from the altered rhyolite in the vicinity of these mines.

THE PAY SHOOTS.

In some deposits ore and ledge matter are practically coextensive; but usually, and particularly in the larger deposits, the ore constitutes a small part of the entire ledge. This is particularly true in the oxidized zone, where the ledges are wide and irregular and where more or less secondary concentration of the gold has taken place. In such ledges the ore may occur within the mass as irregular pods or bunches, or it may lie on one side of a body of ledge matter, with the country rock forming practically one wall.

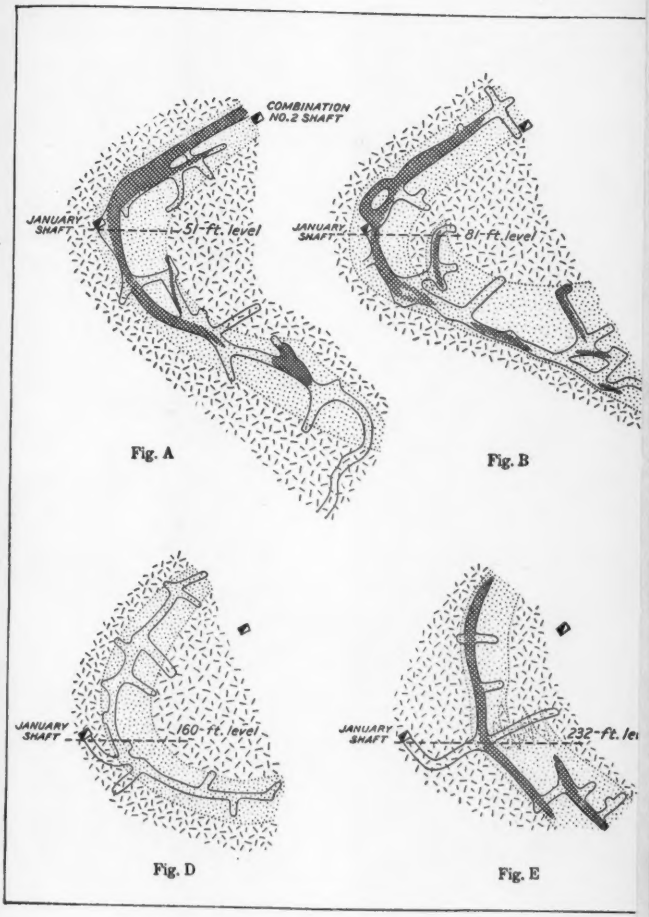
Description of the shape of the Goldfield ore bodies is difficult because the ore bodies themselves are inherently vague. The pay shoots as a rule have no boundaries other than the invisible limits beyond which the assayer's returns show stoping to be unprofitable. The size of pay shoots, and to same extent their shape also, depend, therefore, upon conditions which determine the grade of ore that can be profitably treated at any given time.

In general, the pay shoots are fully as irregular as the ledges with which they are associated. Some of them are roughly equidimensional masses, others are lenticular, some are approximately spindle shaped, with the large axis nearly vertical, and still others are tabular or platelike, although such sheets of ore are often curiously twisted or warped. The striking feature of the ore bodies as a whole is the absence of, rather than the approximation to, any regularity of form. While many of the pay shoots conform to the trend of the inclosing ledge, others do not.

Some idea of the shapes of pay shoots as determined by stoping may be had from Plate V., which shows plans of the ore bodies on successive levels of the January mine, with a generalized section through the workings. The change in form in passing from one level to another is very striking, although the levels are only fifty feet apart. Similar changes are shown in the Combination mine.

PLATE V.

PLATE V.



PLANS OF THE PRINCIPAL LEVELS OF THE JANUARY MINE,

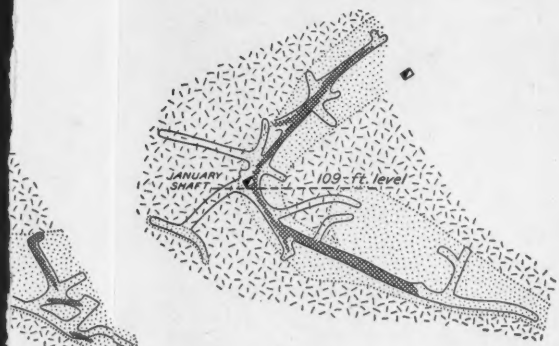


Fig. C

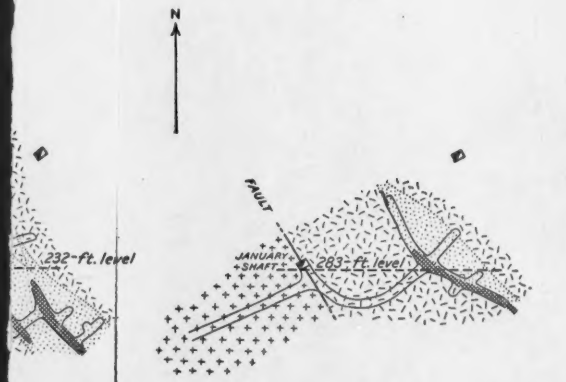


Fig. F

E JANUARY MINE, WITH A DIAGRAMMATIC SECTION SHOWING RELATIONS OF ORE, LEDGE MATTER AND COUNTRY ROCK.

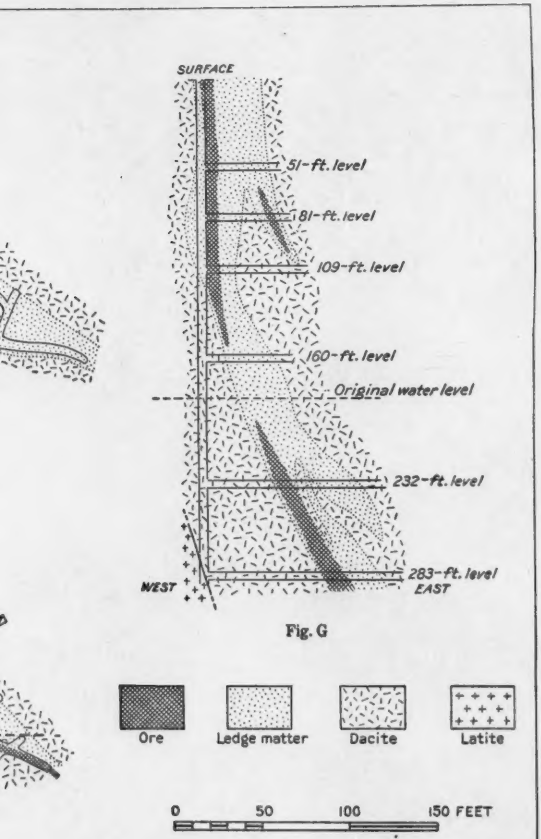


Fig. G

RE, LEDGE MATTER' AND COUNTRY ROCK.

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Beyond the fact that their longer dimensions usually lie nearly in the general plane of the ledge the Mohawk pay shoots have little regularity of form, particularly on the upper levels. Only by long familiarity with the mine or by the aid of a carefully constructed model is it possible to gain any satisfactory conception of the shapes of these pay shoots as indicated by existing stopes. That they are on the whole of flat form and lie generally with the ledge and not across it is shown by Fig. 47.

Among the pay shoots which approach tabular form may be mentioned the southern part of the main shoot of the Combination mine above the 130-foot level, but in spite of the regularity of the ore on this part of the 130-foot level the pay shoot, as shown by Fig. 49 does not extend directly down to the lower levels. The Reilly pay shoot is also of tabular or flat lenticular form, but shows striking changes in dip and strike.

Flattened shoots lying in the plane of the ledge, but with stope lengths so short as to suggest the pipe-like or chimney-like form, occur in the Mushett and Engineers' leases. The pay shoots of the original Little Florence lease also are roughly lenticular with short stope lengths, and, so far as known, do not extend below a depth of 500 feet.

In comparison with such bodies of ore as were taken from stopes in granite in the Portland, Stratton's Independence, and Ajax mines at Cripple Creek, the largest known pay shoots at Goldfield are small. The tenor of the ore mined, however, is much higher than in the Colorado district.

Although metasomatic replacement has played no small part in the formation of the ore deposits as a whole, that process and the ores themselves are very closely controlled by fissuring. Such complete replacement of rock by masses of sulphides as takes place in some limestones, a replacement which in that rock may extend for considerable distances from the fissures supplying the active solutions, is not found at Goldfield. There fissuring, not relative solubility or chemical instability of the country rock, has determined the shape of the deposits. The irregularity of the ore bodies, like that of the ledges, is consequent upon the unusual complexity of the fissuring.

Mere character of fissuring, however, as visible within a few hundred feet of the surface, is only one of several factors determining ore deposition. The district abounds in illustrations of the fact that fissuring, apparently of the most favorable kind, is not necessarily followed by the accumulation of an ore body. The fissure complex must evidently be connected with still deeper channels in such a way as to give access to ore-bearing solutions, and probably also with lateral and superficial channels through which other solutions could pass to mingle with the waters of deep origin and precipitate their valuable constituents. Thus locality and the features of a former topography were probably both of great importance in determining whether a given mass of shattered rock should become an ore body.

That some further modifications of the original shapes of pay shoots take place in the course of oxidation is highly probable, although the steps of such changes can not usually be traced. Oxidation implies changes in volume of the constituents of the mass with more or less gravitative readjustment or settling, minor fissuring, and some migration of material by resolution and redeposition.

So far as known the ore bodies have not as a rule been greatly modified by faulting subsequent to ore deposition. In this respect they differ in striking fashion from the veins of Tonopah. It must be pointed out, however, that the difficulties in the way of the recognition of notable faulting at Goldfield are very great. The ability to recognize important dislocations depends very largely upon the degree to which the faulted structures were initially regular and persistent. When, for example, a well-defined regular vein which has been followed for some hundreds of feet ends abruptly at a fissure filled with attrition products, faulting is at once suggested and in many cases is easily demonstrated. At Goldfield, however, the initial regularity is lacking. The evidence of movement both in and around the Goldfield ore bodies is abundant, but the interpretation of this movement—the discrimination between slips of structural importance and those whose total displacement is measurable in inches rather than feet—is as a rule impossible or inconclusive. If a pay

shoot ends at a seam of gouge, and in a few hundred feet away another pay shoot is found on the other side of a similar gouge-filled fissure, there is as a rule no means of identifying the two bodies as originally part of the same mass, nor can it be assumed in this district, where gouge seams are known to bend through angles of 90° or more, that the gouge in contact with the two masses of ore occupies one continuous fissure.

The difficulty in the way of identifying gouge-filled fissures from point to point by means of a few isolated exposures is well illustrated by the plan (Fig. 50) of the 350-foot level of the Mohawk mine, a level on which the so-called hanging wall of the ledge is visible at more places than elsewhere in the mine. This hanging wall is probably not a single fissure, but a series of fissures, each one of which serves as hanging wall for a short distance and then passes either into ledge or country rock. The significance of this is that the hanging wall is probably as erratic in section as it is in plan. Neither in plan nor section can its true course be drawn from a few isolated exposures.

The conditions as regards faulting may perhaps be best understood by keeping in mind the facts that the ledges as a whole are hard, brittle masses of irregular contour, and that the altered country rock in which they lie is as a rule soft and plastic. The result of any competent compressive stresses applied to the whole system would be to cause more or less slow flowage of the soft country rock around the masses of ledge matter, and in some degree to deform the latter by fracturing or, if the system were much strained, by faulting. That the entire mass of country rock (dacite, latite and andesite) near Goldfield, with its included ledges, has been subjected to stresses capable of effecting such a result will be evident to anyone who examines the exploratory workings of the Kewanas, Combination Fraction, or Portland shafts, or who studies the longer crosscuts into country rock in the principal productive mines. It is the general squeezing which such rock has undergone and the abundance of gouge-filled fissures that constitute one of the chief difficulties in tracing any structurally important fissures through it.

A few faults of small throw have been recognized in the

Mohawk and Combination mines, but these do not materially affect the shapes of the ledges and pay shoots. Probably the strongest indication of important faulting of ore bodies comes from the relation of the Florence ledge to that of the Engineers' lease. In this case it is reasonable to suppose that the Engineers' ore body is displaced about 50 feet to the northeast from the Florence ledge by a curved fault, which dips to the southeast.

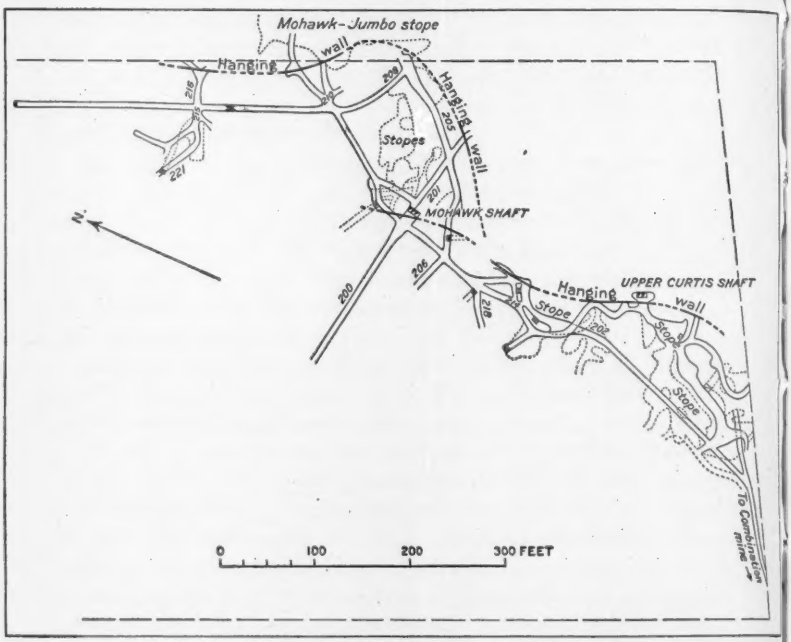


FIG. 50. Plan of the 350-foot level of the Mohawk mine, showing irregularity of the so-called hanging wall.

The possibility that some of the other ore bodies have been extensively displaced by important faults is not denied. It does not appear, however, that there is any evidence now available (1909) which adequately supports such a supposition.

INFLUENCE OF COUNTRY ROCK.

The fact that so many of the larger and better ore bodies are in dacite has naturally made that rock a great favorite with prospectors, and in many cases anxiety to prove its presence has led to the erroneous identification of andesite or latite as dacite. The presumption in favor of dacite as an ore carrier was, however, far greater in 1905 than now, since the Little Florence, Rogers and Engineers' leases have proved that just as good ore may be found in the Milltown andesite as in the dacite. As regards the latite also, recent developments in the larger mines have removed the former prejudice against this rock based upon the fact that no ore bodies of any consequence had been found wholly within it near the surface.

The only ore of consequence found in rhyolite is that of the Sandstorm, Kendall and Conqueror mines. This is oxidized ore, and all efforts to trace it down to workable bodies of sulphide ore have been futile. The probability that large or persistent bodies of ore will be found in any of the rhyolites appears to be small. The ore-bearing capacity of the pre-Tertiary rocks is problematic. As exposed at the surface they contain nothing of value so far as known.

CHARACTER OF THE SULPHIDE ORES.

The typical unoxidized ore as it occurs in the dacite or andesite near Goldfield, particularly in the mines south of the Mohawk, consists of pyrite, bismuthinite and a reddish gray cupriferous mineral having the general composition of an arsenical famatinite, in a dark gray, flinty, quartz gangue. Native gold is usually associated with these minerals, particularly with the bismuthinite and famatinite, and in the rich ore may be easily visible. In ore of the Mohawk type, however, the gold is as a rule less conspicuous. The native gold is in many ores embedded chiefly in the quartz, but it may occur also in minute particles in bismuthinite, famatinite or goldfieldite. The last is a dark gray mineral which according to Dr. Chase Palmer who analyzed it in the survey laboratory, is a cupric suphantimonite in which part of the antimony is replaced by arsenic and bismuth and part of the

sulphur by tellurium. It has provisionally been regarded as a new species and given the name goldfieldite, although it is admitted that the absence of crystal form and the result of the analysis leave the validity of the species open to some question.

Concentric shells of ore minerals about greatly altered rock fragments are rather characteristic of the best ore. Specimens from the Combination mine show an inner zone of free gold and quartz up to an eighth of an inch in thickness. This is covered by a shell of famatinite and this by an outer crust of pyrite. In the Florence mine similar fragments show, first, a shell of pyrite, then one of famatinite, and, finally, a thick crust of quartz speckled with native gold, famatinite, and pyrite, and transfixed by needles of bismuthinite. Some of the particles of gold are embedded in the compact quartz, others are inclosed in the bismuthinite. The different crusts are not in every case sharply defined nor are they necessarily continuous. In the ore of the Engineers' lease two distinct crusts of gold have been observed.

The native gold of these ores is often in particles so fine and so closely crowded in the gangue that the precious metal resembles a streak of yellow ochre, and it is only under a lens that the luster of the particles appears truly metallic. In some of the richest ore from the Mohawk the most valuable crust is a dark gray mixture of goldfieldite, and native gold, closely associated with marcasite.

The ore of the Mushett lease on the Miss Jessie claim northeast of the Red Top mine is structurally and mineralogically one of the most interesting in the district. The proportion of sulphides to gangue is greater than in most of the mines. The metallic minerals noted are pyrite, famatinite, bismuthinite, sphalerite, and a dark gray mineral, probably the provisional new species goldfieldite. This material is rich in gold, specimens which to the naked eye show not a particle of the native metal yielding over $8,000 a ton on assay. The crustification of the Mushett ore is not very regular, but the minerals have formed in the following general succession: (1) pyrite; (2) famatinite, bismuthinite, goldfieldite; (3) sphalerite, and (4) pyrite. The sphalerite in some places forms botryoidal crusts over the prisms

of bismuthinite, which attain a larger size in this ore body than in other known occurrences in the district.

The material forming the extreme outer crust of the nodular ores of Goldfield or filling interstices between the altered and incrusted rock fragments is in most places a soft mixture of alunite and pyrite.

The proportion of silver in the Goldfield ores is usually rather small, the average of thirty-four assays of rich ore from the Mohawk mine, made for Mr. J. W. Finch, at one time general manager, giving 330 fine ounces of gold and 46.5 ounces of silver to the ton. In the Florence mine the ore of the deeper levels contains more copper and silver than that near the surfac. A shipment from the 250 foot level in 1905 contained 100.8 ounces of gold and 3.5 ounces of silver per ton, and 3.5 per cent. of copper.

Tests and chemical analyses of the ore all show a little tellurium, although no tellurium mineral was recognized in the mines close to Goldfield until the discovery of the Mohawk ore bodies. Tellurides of gold, not sufficiently well crystallized for specific determination, and both tellurite and emmonsite (or durdenite) occur near Diamondfield. W. F. Hillebrand has detected some selenium with the tellurium of these minerals. The tellurides are in some cases intergrown with native gold. Most of the analyses of Mohawk ores show about 2 per cent. of tellurium, which is probably due mainly to the presence of goldfieldite.

The common gangue of the unoxidized ore is quartz. This is compact, almost flinty, in texture, although porous in mass, and most of it has resulted from the silicification of dacite, andesite or latite. Large vugs and conspicuously crystalline quartz, such as are found in typical veins the world over, are practically absent from the Goldfield district, where the free development of quartz crystals in open spaces is represented only by drusy films, lining pores left by the solution of phenocrysts, or incrusting small interstitial cavities in brecciated material.

Associated with the quartz in much of the ore are soft white substances that chemical and microscopical tests show to be either

alunite or kaolinite or a mixture of the two. Sericite is rare and is nowhere an abundant or characteristic mineral in the ore deposits. Gypsum, while not known with actual sulphide ore, is very abundant in the altered rocks within a hundred feet or so from the surface, and does occur crystallized with quartz and pyrite in the Goldfield-Belmont mine, below the belt of oxidation.

As a rule, the gold and auriferous sulphides are embedded in quartz. Alunite, however, is often so close to the gold as to appear in the same microscopic field, and a telluride of gold has been noted partly embedded in alunite.

PARAGENESIS.

The paragenesis or order of formation of the minerals in the unoxidized ores is, as in most ore bodies, complex. In general the deposition of pyrite, quartz and alunite appears to have gone on throughout the entire period of ledge formation. On the other hand, there is abundant evidence to show that much of the gold, tellurides, bismuthinite, goldfieldite, marcasite and famatinite were introduced after considerable progress had been made in the special kind of rock alteration which produced the ledges. It appears that some at least of these siliceous masses were fractured and that the richest ores were deposited in the shattered portions.

In some specimens of ore certain of the minerals have formed in definite succession while in others these same constitutents have crystallized together in a single crust. The altered rock on which the first crust is deposited generally contains abundant alunite and disseminated pyrite. In some varieties of ore the boundary between this nucleus and the first crust is definite; in others there is more or less gradation, the disseminated pyrite in some cases becoming more abundant near the surface of the rock fragment and merging with the first pyritic crust. As a rule famatinite has formed before bismuthinite, although both minerals are indiscriminately distributed through some crusts. When marcasite is present as a constituent of rich ore it is closely associated with famatinite or goldfieldite. The free gold or bismuthinite are generally in close association, although in some

specimens the greater part of the gold is of earlier generation than the bismuthinite and in others is later. Sphalerite, galena and marcasite, where present with rich ore, belong to a period of deposition later than that of the gold or gold-bearing constituents.

CHARACTER OF THE OXIDIZED ORES.

Up to about 1907 oxidized ores supplied a large part of the gold produced, and in some mines, particularly the Sandstorm and Kendall, no sulphide ores are yet known. As a rule the oxidized ore is a soft, shattered, more or less earthy material usually stained brown by oxide of iron. Fragments of rusty porous quartz are mingled with kaolin, alunite, gypsum, alum (halotrichite), oxide of iron and various earthy mixtures of no definite mineral composition. Some of the rich ore, as in the Sandstorm mine, is a nearly white, impure kaolin, gritty from the presence of minute crystals or grains of quartz, and containing all through it abundant specks of free gold. Barite, in crystals up to an inch in length, is abundant in this ore, but may be an original constituent. In the Red Top mine some of the richest ore being taken out in 1905 was a firm gritty ocher, of bright yellow color, containing abundant very fine particles of gold. This yellow material is perhaps in part jarosite.[1] In the January and Combination mines some of the most characteristic rich ore consists of porous rusty quartz (silicified dacite), in which the pores and crevices are partly filled with yellow, earthy limonite and tiny pearly scales of bismite, the oxide of bismuth. In some specimens these scales form pseudomorphs after bismuthinite. They are usually a sign of rich ore, but are occasionally found in low-grade or barren material. Halotrichite, a member of the alum group, and alunite are rather abundant in the oxidized ore of the January mine. In the mines of Black Butte the richest oxidized ore usually shows little greenish yellow specks of a ferric tellurite, which Dr. W. F. Hillebrand has determined to be either emmonsite or durdenite. The presence

[1] Spurr, J. E., "Ores of Goldfield, Nev.," Bull. U. S. Geol. Survey, No. 260, 1905, p. 137.

of this mineral shows that the original sulphide ore contained one or more tellurides. Tellurite, a honey-yellow crystalline mineral, which is the oxide of tellurium and should not be confused with the salts of tellurous acid known to chemists as tellurites, was noted in a partly oxidized telluride ore from the Goldfield-Belmont mine near Black Butte. Melanterite (hydrous ferrous sulphate), in some cases mixed with a very little chalcanthite (hydrous copper sulphate), occurs in the partly oxidized ore of the Combination and Florence mines.

The valuable constituent of the oxidized ores is native gold. Native silver and halogen compounds of silver have not, so far as known, been noted in the mines of the Goldfield group, but cerargyrite and probably a little embolite occur in some of the Diamondfield ores. The gold, which has undoubtedly undergone some concentration in the process of oxidation, is in most of the ores finely divided, and even in the richest ores might easily be overlooked by one not accustomed to its appearance. Some of the Sandstorm ore on close examination resembles a fine, somewhat rusty sandstone having gold as the cementing material.

AREAL VARIATIONS IN THE ORES.

Although all of the Goldfield ores have certain mineralogical and chemical features in common, there are some well-marked differences in the ores from different part of the district. Some of the most interesting and important changes are those which may be observed in passing from the Rogers lease at the south end of the Goldfield bonanza belt to the Mushett lease at the north end, a distance of a little less than a mile. By this it is not meant that no rich ore occurs north or south of these leases, but merely that these mark the limits of the most productive area as at present known. From the Rogers lease to the Combination mine the ore of the rich pay shoots is all much alike, although as a rule the product of each mine has slight individual peculiarities whereby one thoroughly familiar with the different workings can identify it. The essential characteristics of this ore are the presence of visible native gold, so distributed through the flinty quartz as to form the dull yellow crusts already described,

the presence of abundant bismuthinite and famatinite, and the absence of recognizable tellurides, sphalerite or galena. The quartz varies in color from nearly white, as in some of the Rogers ore, to a dark gray, as in some of the Engineers' ore.

With the opening of the Mohawk mine ore of a different type was found. In the typical rich Mohawk ore native gold, bismuthinite and famatinite are less conspicuous than in the mines to the south. So far as I am aware this mine has never produced specimens showing such broad bands of finely divided yellow gold as have come from the other mines mentioned. Instead, the best ore has dark telluric crusts which are mixtures of goldfieldite and marcasite. Free gold may or may not be visible.

The change between the typical Combination ore and the typical Mohawk ore is not entirely abrupt, for ore of the Mohawk character has been found in the Combination mine and native gold is abundant on the 740-foot level of the Clermont workings on the Mohawk ledge.

North of the Mohawk mine there is a change to ore of the Mushett type, in which goldfieldite is associated with sphalerite and a little galena.

From the Mushett lease to the mines near Diamondfield there is an interval of about three miles, in which no rich sulphide ores of any consequence have been found. Mineralogically the Diamondfield ores resemble those of the Mushett and neighboring leases rather than those of the mines south of the Mohawk. Most of them, however, are soft crushed masses with little of the interesting crustification which is so marked a feature near Goldfield. The proportion of sulphides to gangue is less at Diamondfield than in the Mushett lease.

East of the Rogers lease is another gap of three-quarters of a mile to the Gold Bar and Victor mines, which have still another variety of ore. The best of this is of relatively low grade. The cupriferous constituent, which is abundant, is apparently nearer to enargite than to famatinite. No tellurides have been recognized, and neither visible native gold nor bismuthinite is common.

OBSERVED CHANGES IN DEPTH.

Observations to determine what changes, if any, take place in the unoxidized ores with increase of depth are limited to a vertical range of about 850 feet, which is the distance from the base of the oxidized zone to the bottom of the Clermont mine. Within this range the mineralogical changes are not very marked. The minerals associated with the very rich ore at depths of 200 or 300 feet have been found also at lower levels. Alunite, as a constituent of the altered rocks, is as abundant in the deepest parts of the ledges yet reached as it is nearer the surface, and it appears from this that there was no essential change in the general chemical character of the ore-bearing solutions. As a soft interstitial filling, however, the mineral is slightly less abundant on the lower levels than it is on the higher levels. The explanation of this is thought to be physical rather than chemical. It is to be expected that spaces formed by fracturing in the deeper parts of a ledge would be smaller and less numerous than where the strained material is under a lighter load.

Some pay shoots have shown a decided diminution in value before reaching a depth of 500 feet, but the changes in both horizontal and upward directions from the kernel of a bonanza may be fully as notable, and where deposits have shown themselves to be so irregular as those of Goldfield caution is prescribed in deducing a general law from a few examples. In the Clermont workings excellent ore in latite was exposed in 1909 on the 860-foot level and the same rock in the shaft at a depth of 1,000 feet shows much alunitization.

On the whole and without special reference to any particular mine, observation indicates a general although not uniform decrease in the tenor of the ores in the deeper workings. The gold, goldfieldite, bismuthinite, and, to a less extent, famatinite become less conspicuous, while pyrite is relatively more abundant.

ORIGINAL DEPTH OF THE ORES NOW VISIBLE.

The dacite near Goldfield rests partly on the Milltown andesite, but mostly on latite. Immediately after its intrusion, therefore, the dacite may have been covered by the greater part, possibly

700 or 800 feet, of the Milltown andesite. This cover was doubtless much broken by the force of the intrusion, and in consequence was easily eroded. The presence of abundant dacitic fragments in the basal part of the Siebert formation between Goldfield and Columbia indicates that before the lacustral epoch closed the dacite had been laid bare and was being actively eroded. The presence of this coarse littoral material suggests further that the site of the future mines was not one of the deepest parts of the lake, but for a time at least was unsubmerged land. At the close of the lake epoch, therefore, the present productive area of dacite must have been buried under considerably less than the 1,000 feet of sediments estimated as the maximum local thickness of the formation. With the disappearance of the lake, erosion began, and this may have further thinned the overlying sediments before ore deposition ceased. At the most, however, this erosion did not reduce the surface below the general level of the peneplain at the base of the Spearhead rhyolite, since the completion of the peneplain, as shown by alunitized fragments in the Pozo formation, must have been subsequent to ore deposition. A rough restoration of this plan over the site of the present mines would carry it about 300 feet above the existing surface of the dacite, indicating at least that amount of erosion since the ores were deposited.

On the whole, therefore, and without reference to any regional changes of level, it appears that the surface of that part of the district containing the principal ore bodies was not more than 1,000 feet higher than at present, and the difference may have been some hundreds of feet less. The general geologic relations of the deposits, therefore, indicate comparatively superficial origin.

The structure and the mineralogical character of the deposits point to the same conclusion. The intricacy, irregularity, and lack of persistency of the fissuring are indicative of rupture under small load. The change in tenor of the ores at moderate depths is suggestive of deposition controlled in part by proximity to the surface. The presence of cinnabar and native sulphur not, it is true, in the ore deposits themselves, but in the same

province or region, is, as De Launay[1] has shown in his study of the Italian metallogenetic provinces, and Villarello[2] for the metalliferoue regions of Mexico, in harmony with the view that the ore deposits were formed in a comparatively superficial zone. The presence of abundant antimony, bismuth, and tellurium, and the extraordinary richness of the Goldfield ores have similar significance. Like the deposits at Cripple Creek, those of Goldfield exhibit a mineralogical character that is suggestive of origin through processes connected with volcanism and active at moderate or slight depth. The original surface at Cripple Creek was probably from 2,000 to 5,000 feet above the present one. The erosion at Goldfield has certainly been much less.

AGE OF THE DEPOSITS.

How merely tentative is the application of the Tertiary chronologic scale to the Goldfield deposits has already been pointed out. In terms of this provisional usage the age of the ores is late Miocene or early Pliocene.

METASOMATIC PROCESSES.

Three types or stages of alteration are recognizable. Where the chemical activity has been most intense the rocks have been changed to porous, fine-grained aggregates consisting essentially of quartz. This is the material of which are composed the hundreds of craggy points and ledges that are characteristic of the topography of the district. Although most of these ledges, so far as known, contain no ore bodies, yet until recently no ore has been found that was not in or alongside such quartz rock. Some of the discoveries made in 1906, however, show that very rich bodies of ore may occur at places where there is no siliceous outcrop.

The second type of alteration is one in which the rock is changed to a comparatively soft, light-colored mass of quartz,

[1] "La métallogénie de l'Italie," Cong. géol. intern., Mexico, 1906, *Compt. Rend.*, vol. 1, 1907, p. 561.

[2] "Sur le remplissage de quelque gisement, métallifères," Cong. géol. intern., Mexico, 1906, *Compt. Rend.*, vol. 1, 1907, p. 548.

kaolinite, alunite and pyrite. At any given locality the boundary between the rocks representing the two kinds of alteration may be fairly sharp; but the proportions of quartz, kaolinite and alunite vary widely, and consequently, over the field at large, gradations in composition and hardness may be found between these two typical metamorphic products. Both types are usually associated with the ores and are most conspicuously displayed over a belt of country stretching east from Goldfield past Preble Mountain.

The third type of alteration has effected less conspicuous results than the other two, and its products are not closely associated with the ores. It consists in the development of calcite, quartz, chlorite, epidote and pyrite at the expense of the original minerals and groundmass, and is thus propylitic in character. Rocks which have undergone this form of alteration, chiefly andesite, latite and dacite, still retain something of their original color and texture, the principal external sign of change being a greenish tint instead of the usual dark gray of the fresh rock, and a lack of luster in the phenocrysts.

The propylitic type is rather sharply marked off from the alunitic type by the presence of calcite and by the usual absence of alunite, these minerals having been observed together only at one place, on the east slope of Vindicator Mountain, where very minutely crystalline calcite, sericite, and probably some kaolinite have been found associated with much larger crystals of alunite in altered rhyolite. The occurrence together of alunite and calcite, apparently developed simultaneously, shows that the alteration took place under conditions which did not permit the free escape of carbon dioxide. It is scarcely conceivable, for example, that calcite could form in the presence of sulphuric acid percolating down from an overlying deposit of oxidizing pyrite.

The alteration of the alunitic type is not confined to the vicinity of known ore bodies, but is prevalent over wide areas not recognized as ore bearing. The general relation of ore bodies to alunitization is shown in Fig. 4, in which the area affected by alunitic alteration is indicated with as much accuracy as is possible where there is no real boundary to be shown.

The character of the alunitic alteration has already been fully described.[1] It will be sufficient in this place to indicate the general nature of the change in the dacite by the diagram shown in Fig. 51.

The metamorphic agent was evidently a strongly acid solution carrying sulphydric and sulphuric acids, and possibly sulphurous

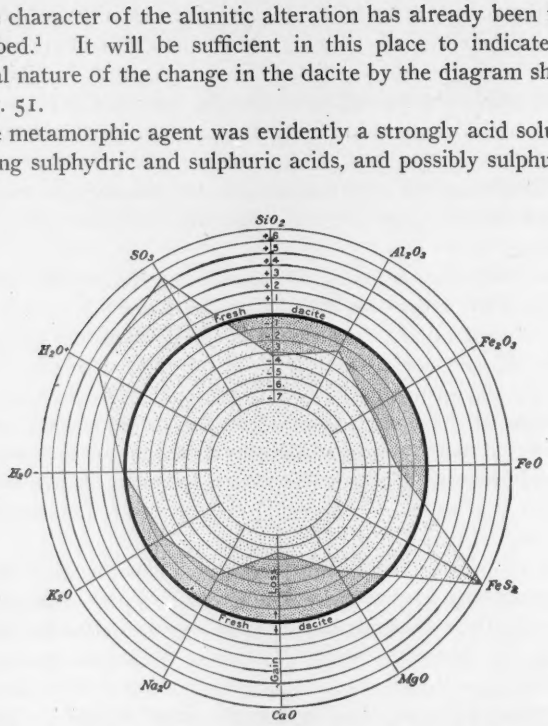


FIG. 51. Diagram illustrating gains and losses of each chemical constituent in terms of percentage of mass of original fresh dacite. Radial distance between successive circles corresponds to 1 per cent. Gains are outside, and losses inside, of the heavy circle representing fresh dacite. Areas have no significance.

acid. The solution was capable of decomposing the silicates in the rocks, carrying part of their constituents away, reacting with the iron of the magnetite and silicates to form pyrite, with the potassium and aluminum to form alunite and with the aluminum

[1] "The Association of Alunite with Gold in the Goldfield District, Nevada," This journal, vol. 2, 1907, pp. 667–692, also in Professional Paper U. S. Geol. Survey, No. 66.

to form kaolinite. The large percentage of loss in calcium, potassium, and sodium shows that the active solution was far below its saturation point for these elements, and was therefore, within the range of depth investigated, entirely different in character from the alkaline solution which deposited the large class of sericitic and calcitic gold-quartz veins exemplified by those of California.

Not all of the dacite is altered to exactly the same product as that just described. Some varieties contain diaspore as a microscopic constituent. Others, which may be classed as ledge matter or ore rather than country rock, contain more quartz and pyrite. On the south slope of Preble Mountain, near the summit, the dacite in some places has been altered to a white fine-granular rock, not unlike quartzite or marble in general appearance. This is a nearly pure aggregate of quartz and alunite, with very little pyrite. The original texture of the rock, except for the presence of an occasional phenocryst, is entirely obliterated.

GENESIS OF THE DEPOSITS.

Three hypotheses of the mode of formation of the Goldfield ores have been considered. The first, which may be called the direct volcanic hypothesis, postulates that the ores were precipitated from hot, originally acid solutions emanating from some deep-seated body of solidifying magma. For a discussion of the evidence for and against this view the reader is referred to Professional Paper No. 66. The principal objections to it are that solutions effective in producing other deposits of the precious metals are known to have been of a different kind and that it is doubtful whether acid sulphate solutions are efficient solvents and carriers of gold, sulphides and tellurides.

The hypothesis that the alunitization of the rocks at Goldfield was effected by cold sulphate solutions percolating generally downward from masses of oxidizing sulphides, principally pyrite, has some facts in its favor. The small quantity of impure alunite found at Cripple Creek was undoubtedly formed in this manner, and observations indicate that a part of the alunite at Goldfield, namely, some of the soft varieties which fill inter-

stices in the partly oxidized ore, may have been, if not originated, at least dissolved and redeposited during oxidation. According to De Launay[1] the alunite at the classic locality of Tolfa is the product of such solutions acting upon a particularly feldspathic trachyte. The formation of alunite by cold percolating solutions probably requires these to be more strongly acid than is necessary for the production of kaolinite.

The principal objections to the view that the alunitization at Goldfield is connected with the oxidation of older pyritic ores are based largely on what appears to be the quantitative insufficiency of the proposed explanation. No such available primary masses of sulphides are known, and study in the district has failed to bring to light any bodies of sulphides that are distinctly older than the ores and that are not accompanied by alunite. There is no evidence yet found which indicates the superposition of a distinctly younger phase of deposition characterized by the formation of alunite upon an older phase not associated with that mineral. The mines at Goldfield are still comparatively shallow, but they have penetrated about 900 feet below the bottom of the weathered ores, and if the alunitization were the result of ordinary weathering it is likely that secondary products would somewhere have been found distinctly imposed upon earlier non-alunitic material. It is probable that at a depth greater than that now attained alunite will become less abundant, but the change will, it is believed, be gradual, and there is nothing to indicate that it will exhibit such a definite relation to the general ground-water level as might fairly be expected under the hypothesis now under consideration.

The alunitization of the rocks, as shown by Plate IV., is very extensive and is by no means confined to the immediate vicinity of known ore bodies. Except in the zone of superficial oxidation the alunite is crystallized with pyrite and consequently has not formed under conditions involving the destruction of this sulphide in the zone now accessible. To account for the alunitization by the oxidation of pyrite would require the assumption that

[1] "La métallogénie de l'Italie," Cong. géol. intern., Mexico, 1906, vol. 1, 1907, p. 681.

the material stripped from the district by erosion was much more heavily pyritized than the rocks at present visible. The thickness of this vanished overburden, as has been shown, can scarcely have exceeded 1,000 feet and probably was very much less. Moreover, the period available for alunitization was geologically very brief, since the process had already taken place when the Pozo formation was laid down. We are thus confronted by the contrast of a process remarkable for the extent and intensity of its action with conditions which, if not markedly unfavorable, were at least not such as would be expected to produce the observed effects under the present hypothesis. The remarkable concentration of the gold and associated minerals in these deposits appears to be out of all proportion to any leaching action possible within the time and distance available. This discrepancy becomes more marked when the character and genesis of the metallic minerals of the ores are considered.

In accordance with the third hypothesis, that of simultaneous solfatarism and oxidation, it is believed that after the intruded dacite had solidified, but possibly before it had entirely cooled, the district and part of the surrounding region was subjected to stresses that found relief in a very complicated system of fissures, which were unaccompanied by any considerable displacement of the rocks. Hot waters carrying abundant hydrogen sulphide with some carbon dioxide and the various metallic constituents of the ores rose in these fissures. The dissolved hydrogen sulphide was oxidized in part to sulphuric acid in the upper parts of the fissure zones and at the surface. The resulting acidic solutions percolated down through the shattered rocks, changing their feldspars to alunite, mingling with the uprising sulphide solutions, and precipitating the greater part of their metallic load as ore. The original solutions apparently were not everywhere equally rich in gold, since in many parts of the district ledges were formed which have not proved to be of any value. The most highly mineralized waters rose along a north-south belt about three-quarters of a mile in length and along the line of the Columbia Mountain fault, near Goldfield. Just what significance should be attached to this coincidence of fault and

mineralization is not clear. As suggested on page 310, the fissuring along this belt may have been occasioned by a renewal of movement along the predacitic fault line. The presence of the fault fissure may also have favored deep connection with the ore sources. These suggestions, however, are not susceptible of proof and would have more weight did not some good ore occur in other parts of the district.

It is believed that during this first stage of deposition most of the ledges were formed, much of the country rock was softened and alunitized, other parts farther from the fissures were propylitically altered, and some masses of good ore were deposited.

The ledges at this time were presumably harder than the altered rocks which inclosed them, and it would seem at first thought that any subsequent fissuring would avoid the siliceous masses and pass through the softer material. To some extent it probably did so, the stresses finding relief in gouge-filled, curved, and irregular slips through the country rock. Movements in the soft country rock, however, which is more or less plastic near the ledges, could not fail to exert on these rigid brittle masses stresses which would deform them, like the quartz pebbles in some squeezed and schistose conglomerates, by many small fractures rather than by a few simple fissures. The fractured ledge masses would be pervious to solutions, while the surrounding squeezed country rock would be relatively impervious. Some ledges after fracturing were perhaps cut off from communication with the rising mineralizing solutions and are to-day comparatively barren. Others to which these waters had access, particularly those in which considerable sulphide decomposition had previously taken place, were enriched by the revival of the circulation of hot ascending sulphide solutions and cooler descending sulphate solutions mingling in the manner already described. The conditions during this second stage of mineralization would probably be more favorable for the concentration and deposition of very rich ore than during the first stage. The shattered ledges may be likened to great sponges in the pores of which were provided ideal conditions for chemical reactions and

precipitation, the sulphides already formed probably aiding directly in withdrawing gold and fresh sulphides from solution.[1] It is not necessary to supose that all the ledges were subjected simultaneously to this second fissuring or that all were affected by the same number of recurrent depositions. The richest ore bodies probably occur in those ledges which were most often fractured and which at the same time retained most continuously an open connection with the deep sources of the hot sulphide waters. Movements in the ledges have continued up to very recent times and may be still in progress. They are no longer followed, however, by any manifestation of thermal action, although they have afforded opportunity for some minor enrichment by waters which have passed downward through the belt of weathering.

If the explanation here given is correct it follows that the conditions for the formation and preservation from erosion of deposits of the Goldfield type must be rare. Climate alone may exert a controlling influence. If the original sulphide solution rose in a region of abundant rainfall, deep soil, and luxuriant vegetation, oxidation of the hydrogen sulphide to sulphuric acid would take place less rapidly, and most of the acidic solution, instead of sinking deep into the ground, might flow off in streams. Such part as did seep down and survive the reducing action of organic compounds would mingle with a ground water diluted by copious rains and too rapidly renewed by run-off and additions to be of great chemical activity.

In a region of rapid erosion the entire zone of alunitization might be removed in a geologically short time and deposits of no unusual character be left.

GOLDFIELD TYPE OF DEPOSIT.

The recognition of alunite as a characteristic constitutent of the Goldfield ores and the demonstration of its genetic relation to them establishes a new type—that of alunitic and kaolinitic gold-quartz veins—in the classification of epigenetic deposits based

[1] See Clarke, F. W., "The Data of Geochemistry," Bull. U. S. Geol. Survey, No. 330, 1908, p. 558.

upon the kind of metasomatism effected in the wall rock by the ore-depositing solutions. While the Goldfield deposits are probably too irregular in form to come under the usual definition of vein, yet in all that relates to genesis of the ores there is no essential difference between them and what is usually termed a metasomatic fissure vein. Moreover, the tendency for the ledges to become more regular and lodelike with increasing depth, pointed out in Professional Paper No. 66, page 154, is reported to be apparent in workings opened since that report was written.

KEWEENAWAN COPPER DEPOSITS.

FRANK F. GROUT.

The southwestern extreme of the Keweenawan area has been the subject of detailed study by the Minnesota Geologic and Natural History Survey for the past two years, and the writer has had opportunity to make some tests bearing on the source of the copper. The continuity of geologic formations should make the conclusions applicable to the Keweenaw Point ore deposits.

It is largely due to these geologic relations, that test pits and prospect shafts have been opened in places on every easily accessible stream in the Minnesota area. The most extensive work has been on Snake River, where the exploration was carried down several hundred feet. In this and several other places, copper is found in quantities sufficient to keep up the enthusiasm of the optimistic prospectors. Its association varies. On Snake River numerous small masses of copper fill the irregular spaces in a vein of red laumontite, especially near the contact of the wall rock, a compact trap. On the dumps of the two shafts, however, there is a good field for mineral collection and the locality becomes interesting. Datolite was a new discovery for Minnesota (later found elsewhere in the Keweenawan). The abundant laumontite is altering to a mineral of very exceptional composition, a pseudolaumontite, potassium and magnesium having replaced all the lime of the original. There are also found calcite, quartz, orthoclase, analcite, chlorite and the essential minerals of the diabase. On Kettle River a recent shaft follows a breccia, in which copper occurs as fine grains scattered in prehnite, and a similar list of less abundant associates. On several creeks a red laumontite pseudoamygdaloid has been explored on account of a few small nuggets of copper seen in it near the surface. One abandoned dump shows veins of copper in calcite.

J. F. Kemp presents the views commonly accepted[1] in discussing the copper deposits. The copper is such a characteristic associate of the Keweenawan lavas that it is easy to conclude that it was brought to its present neighborhood as a part of the molten lava. Both the overlying sediments and the underlying unknown—"below"—have been suggested as possible sources. A study of the mineral association led Smythe to uphold the latter theory. The evidence may be summarized as follows: Pumpelly's study of the paragenesis indicates that the early minerals are such as would be expected from the decomposition of such a rock as diabase—the non-alkaline silicates, calcite and quartz. Copper is associated with the later silicates which contain much alkali and some boron—in datolite. The diabases are low in alkalies, and no chemical test is delicate enough to find traces of boron in silicates. Copper in the fresh diabase has been recorded only as scattered grains of a sulphide, and these are not clearly original. Such ancient rocks may have been infiltrated to that extent. Hence, Smythe concludes the copper and its associates are derived from depth, while the non-alkaline silicates result from the wall rock. In answer to this it is contended that the really characteristic associate of copper is prehnite, which is supposed to be a product of the trap; not datolite, which is comparatively rare. Whatever the source, it is generally agreed that copper was deposited from water solution in its present position.

Van Hise, finding copper associated with the cementing minerals of the belt of cementation, assigns it the same origin, from *ascending* solutions. However, these ascending solutions may not have come from a remote source, for he says:[2] "Copper is disseminated throughout the Keweenawan lavas of the whole Lake Superior Basin. This has much greater significance to me, with reference to the source of the metal, than does the association of the ore with an igneous rock at a particular mine."

F. W. Clarke says:[3] "Native copper is commonly if not always

[1] "Ore Deposits of United States and Canada," 3d ed., 1900, p. 209.
[2] U. S. G. S., Mon. 47, p. 1033.
[3] U. S. G. S., Bul. 330, p. 565.

a secondary mineral. In the Lake Superior region . . . its original home, perhaps as sulphide, was in the unaltered igneous rocks. It is now associated with other minerals of hydrous origin."

Given a solution of copper, the precipitant has been assumed to be a ferrous compound, since Pumpelly found oxidized iron common in associated minerals. The ferric chlorite, delessite, is most prominent. Not much further evidence can be given on this point. It might be noted that the delessite analyzed from Minnesota localities has less ferric iron than the samples from Michigan; but, on the other hand, the Snake River laumonite associated with copper, has a high ferric impurity and the prehnite, characteristic of copper "ores" of Kettle River, has 5.45 per cent. of ferric oxide, at least a part of which enters the compound replacing alumina.

The most doubtful points seem to be the source of the copper, and if in the lava, what relation it bears to the rock.

The Keweenawan in Minnesota reveals a complex part of the syncline characteristic of Lake Superior. Outcrops are not abundant, as the red sandy gravel of the drift averages about 75 feet in thickness over the area. In this red drift along the St. Croix River are extensive deposits of a laminated red clay. This is used at Grantsburg, Wis., for a fair quality of brick, and the material seems to be uniform in all the exposures.

Rocks of the region include the various types of diabase, well known at Keweenaw Point, and the Snake and Kettle River series include conglomerates. In two or three parts of the district volcanic tuff and breccia occur. The present investigation involved a detailed study of the diabases, which are classified in three groups on the basis of field characters and texture—the mottled type with an ophitic texture, the hackly fracturing (common) type with diabasic texture, and the conchoidally fracturing type with granular texture. The field characters and texture are found to correspond approximately with a change in the proportion of augite to plagioclase in the diabase—highest in the mottled and lowest in the conchoidal type. However, without leaving the Keweenawan formation, one may find nearly all

gradations between these types. Olivine, though present in a few and represented by pseudomorphs in many samples, is not a good mineral to use in distinction of rock types as ancient as these. It is so readily and extensively altered that many samples would be left in doubt. Olivine probably existed in some rocks of each of the three types here described, but not necessarily in all the rocks of each type. The only relation heretofore suggested between these rock types and the copper ores is a rumor that in Michigan it is considered a favorable sign, if a prospect is located near a mottled flow (variously called melaphyr, greenstone, etc.). Tests have been made on several samples for minute quantities of copper. The great number of microscopic and chemical tests conducted made it possible to select such samples as would give most valuable information.

The first selection was a series of specimens of one type, showing different stages of alteration. Unfortunately no material was available to allow tests of a single flow in various stages of alteration, but random samples chosen from one type, solely by their degree of alteration, may be taken as fairly good indication of what may be expected in more extensive study. The freshest Keweenawan rock examined was of the common hackly type, and this type was therefore chosen for the series.

EFFECT OF ALTERATION.

	Per Cent. Copper.
1. Hackly Diabase, Pine City, Minn. Very Fresh	0.029
2. Hackly Diabase, Crooked Creek, Minn. Average alteration	0.020
3. Hackly Diabase, McDermott Creek, Minn. Extreme alteration	0.013

The second selection was designed to show the possible relation between the type of diabase as given above, and the amount of copper. Material was chosen showing average alteration, though there was no certainty of the exact equivalence of the effect in different samples.

EFFECT OF TYPE OF DIABASE.

	Per Cent Copper.
4. Mottled diabase, Taylors Falls, Minn.	0.019
2. Hackly diabase, Crooked Creek, Minn.	0.020
5. Conchoidal diabase, Crooked Creek, Minn.	0.012

These results were obtained by the use of 10 grams of rock decomposed with sulphuric and hydrofluoric acids. The copper was twice separated from the dilute sulphate solution by means of hydrogen sulphide, after which further traces of iron were removed by precipitation of the nitrate solution with ammonia. At this point an approximate estimation of the amount of copper was made on the basis of the intensity of the blue color. This was checked later by the intensity of the ferrocyanide coloration in very dilute acid solution. A blank determination was perfect, but a series of determinations of known minute quantities indicated a loss of copper equivalent to about 0.002 per cent.; the values in the tables may be a trifle low.

A third test was designed to show the condition of the copper in these rocks. So far as recorded, the minerals commonly precipitated from copper solutions are soluble in nitric acid. Sample number 2 of the table which contained 0.020 per cent. copper, yielded only 0.002 per cent. to digestion in nitric acid.

CONCLUSIONS.

1. Copper does occur in all the types of Keweenawan lava, even where not visible as distinct copper minerals, even microscopically.

2. The fresher the rock, the more copper is present. The few tests made may not be sufficient to conclude that the "last word has been said," but it seems probable that future work will confirm the result. The removal of copper during alteration is to be expected, if we accept conclusion 3.

3. The copper of the fresh rock is in the form of an insoluble silicate, rather than a sulphide or native copper. Such a compound is not rare, as evidenced by the accumulated literature.[1]

4. The rocks with a large proportion of basic silicates should be more favorable than others as a source for copper accumulations. This is a more doubtful conclusion, though confirmed by observation. Other effects, like the amount of alteration, are clearly more important. The trunk channels and good precipi-

[1] See U. S. G. S., Bul. 330, p. 542.

tants are more active in locating an ore body than the slight increase in original concentration. The mottled rocks, however, furnish not only a high percent. of copper, but more ferrous iron for a reducing agent than the other types.

5. Quantitatively, these percentages of copper are sufficient to account for the formation of an ore, only under rather extremely favorable, though not at all impossible, conditions. This can be illustrated. If all the copper in a flow 100 feet thick were gathered into a layer over one tenth of the surface of the flow, that one tenth would be workable ore. When one considers the small thickness of flows, the scattered nature of the amygdaloidal zones, and the small proportion of copper which is likely to enter circulation, the absence of ore deposits in much of the Keweenawan is not surprising.

DISCUSSION

This department has been established by the editors in order to afford to those interested in questions relating to economic geology an opportunity for informal discussion. Contributions are cordially invited either in the form of discussion of more formal papers appearing in earlier numbers or bearing upon matters not previously treated. Letters should be directed to the Editor, Sheffield Scientific School of Yale University, New Haven, Conn. The full name of the author should be attached to all communications.

CRITERIA OF DOWNWARD SULPHIDE ENRICHMENT.

DISCUSSION OF PAPER BY F. L. RANSOME.

Sir: Mr. Ransome has rendered a distinct service to the science of ore deposits in bringing together in an orderly and philosophic arrangement the criteria by which one may recognize whether a given association of ore minerals have been enriched by downward migration of the upper part of the deposit. While we have undoubtedly much still to learn, especially from the chemical side, with regard to this process which plays so important a part to-day in our valuation of ore deposits, it was very necessary that some one should have the courage to critically discuss the knowledge that we already possess, and this he has done in the thorough and systematic manner that characterizes his work in general. I can take no exception to anything that he has said on this subject, and can only offer a few thoughts that may be of value rather as suggestions for the investigation of younger and more active workers than as completely determined facts.

I am glad to see that he admits that the association of kaolinite with metallic sulphides constitutes an *a priori* ground for assuming downward enrichment, for it was the presence of a wet kaolin mud in the secondary fractures of the Butte veins that first proved to me that the moisture in the fractures necessarily

came from the surface, my underground experience having long ago convinced me that in ore deposits, at any rate, kaolinization, in the vast majority of cases, results from the action of surface waters.

While secondary or post-mineral fractures are a most important indication of probable downward migration, they are not absolutely essential, since as he well says "the impermeability of an ore body is never absolute." This is most evident in the district of Cobalt, Ontario, where the rocks are unusually dense; yet the evidence of secondary enrichment there is most striking. The most important criterion in this district is one which Ransome does not seem to have mentioned — viz: the suddenness and magnitude of the change from the bottom of the enriched zone to the primary unenriched ore. Thus, an ore carrying 2,000 to 3,000 ounces in silver passes in twenty feet or less into an ore carrying not over ten ounces on the average. This means that an immense amount of erosion must have taken place to enrich the ore to such a degree. That the native silver fills cracks in previously formed cobalt minerals, is readily discernible even to the naked eye, but this cannot be explained, as has been attempted by some, as simply due to the later introduction of silver from below. It is only on the theory that it is the result of the downward enrichment of an immense thickness of rocks, hence the concentration of great extents of veins now eroded away, that the magnitude and abruptness of the change can be explained. In general, therefore, where the change in values is too great and sudden to be explained by uprising solutions, downward enrichment must be assumed.

Mr. Ransome's paper deals only with sulphide enrichment, for the reason that in the vast majority of primary ore deposits the metals are combined with sulphur, but there are districts, notably that of Cobalt just referred to, where they are mainly combined with arsenic and antimony. The determination of how far their action corresponds with or differs from that of sulphur combinations, affords an interesting field of study.

With regard to the more precious metals, gold and silver, less is definitely known of their chemical actions, because they are

so frequently in quantity or combinations in which they are not visible to the naked eye. Mr. W. H. Emmons has recently completed a most interesting study of the chemical conditions under which gold may be transferred by cold dilute mine waters, in which he shows the importance of the presence of a small amount of manganese, whose action upon chlorides may produce nascent chlorine which directly combines with gold, forming a soluble chloride. This throws light on many hitherto unexplained phenomena of gold deposits; among others, the presence of rich pockets of gold-bearing material in the Cambrian quarzite of Leadville below where any other ores are found. His paper will appear in a forthcoming number of the *Transactions of the American Institute of Mining Engineers.*

S. F. EMMONS.

Sir: The paper of Mr. F. L. Ransome in the April number of ECONOMIC GEOLOGY upon "Criteria of Downward Sulphide Enrichment" is certainly a most useful elucidation of the general aspects of such enrichment. I should like to present a few thoughts, chiefly of a chemical nature, which were suggested by his paper.

Mr. Ransome's observations are presented as general ones and I do not wish to make any objections to them but merely to enlarge somewhat on the chemical side of the question. It seems to me that one of his geological criteria—that the change in the ores should be dependent on oxidation—is really chemical and of fundamental importance. Whereas he considers the chemical criteria in the narrow sense of progressive changes shown by assays or analyses, it might perhaps be possible to make a few generalizations along the line of the chemistry of the process of enrichment, which would cover various metallic deposits. Of course most is known about copper. Although each metal will always have to be considered largely by itself, possibly certain generalizations can be suggested.

The processes of secondary enrichment involve (1) solution, (2) transportation and (3) deposition. The essential chemical processes of solution take place near the surface because there

the environment is oxidizing and when bisulphides or polysulphides are present also acidic. There are other chemical factors than oxidation upon which secondary enrichment may depend in special cases, for example, the presence of carbon dioxide, which must exert a solvent action, and of chlorides and nitrogen compounds brought to the ground by rain water, which might play a rôle in the transportation of gold and of the synthetic products of plants and animals at the surface, which might aid processes by concomitant action and act as carriers. All of these substances are characteristic of the "upper zone," but must, however, leave only indistinct marks of their passage through it. In general a leached residue is the only visible criterion by which to judge of their operation unless iron was present and has left its mark as limonite. The reason iron tends to remain is because ferric salts hydrolyze into basic sulphates with great readiness.[1] Chemically one would expect aluminum and titanium to appear in the same class, but although minerals of these elements undoubtedly result from leaching processes they are not as valuable criteria as limonite on account of lack of color. It is well known that titanium becomes concentrated by leaching alteration. In an extreme case xanthitane seems to have so resulted. Gibbsite, diaspore and kaolinite are more common.

Recently Buehler and Gottschalk[2] have shown that the oxidation of galena, sphalerite, covellite and enargite takes place more rapidly in the presence of pyrite than otherwise. This, it seems to me, is to be ascribed to the free acid produced by the bisulphide and I am inclined to lay considerable stress upon the production of acid solutions by polysulphides. It would seem unlikely that free acid would be produced from other sulphides. Although Buehler and Gottschalk give no explanation of the accelerating effect of pyrite upon the solution of the sulphides they investigated, it seems to me that the explanation is that free acid is produced by the pyrite. The bearing of these facts is

[1] "The Hydrolysis of Ferric Sulphate," R. C. Wells, *J. Am. Chem. Soc.*, 1909, 31, 1027.

[2] ECONOMIC GEOLOGY, 1910, 5, 28–35.

merely to emphasize Ransome's statement that the presence of an oxidized cap suggests that enrichment will be found below, particularly, residual oxide of iron would seem to be the best clue to a leaching process, a process which would be likely to concentrate copper, zinc, silver and gold if they were in the original strata.

Under the head of transportation it may be mentioned that the processes involved are really only stages in shifting equilibria. In an oxidizing or acid environment the tendency is toward solution, in the neutralizing or reducing environment the tendency is toward deposition. The limiting stages are reached only at the extreme confines of the field of operation. In *all* regions, so far as geological operations are concerned, equilibrium is probably nearly obtained at any given time.

In thinking of these equilibria I have tried to generalize the behavior of various salts by what might be termed the principle of compatibility. By this is meant that under a certain definite set of chemical conditions the elements will tend to enter into combinations corresponding to those conditions. The idea is particularly applicable to oxidation and reduction phenomena. To illustrate by a simple example, stannous chloride and mercuric chloride in solution tend to rearrange themselves into stannic chloride and mercurous chloride. The two latter compounds are compatible, but not the former. With an excess of stannous chloride, mercury is the compatible product. Many such instances might be mentioned. For instance in an environment where acid solutions exist, iron, manganese, zinc and all carbonates will tend to pass into solution; in an alkaline environment most of the metals tend in general to be precipitated from solution. In an oxidizing environment sulphides tend to pass into sulphates. Here again the specific sulphide must be considered. For example, the full oxidation of copper sulphide produces only copper sulphate, but the full oxidation of a bisulphide produces free acid also and the oxidation of lead sulphide produces insoluble lead sulphate. The necessity of unlimited chemical study of special cases, in regard to compatibility, may be illustrated by the case of $CuSO_4$ and $FeSO_4$. While studying

mixtures of these two soluble salts I noticed that iron oxide was precipitated on warming. This occurred so much more easily in the presence of $CuSO_4$ than with $FeSO_4$ alone that I was led to suspect that there was an equilibrium of the following nature:

$$2CuSO_4 + 2FeSO_4 \rightleftharpoons Cu_2SO_4 + Fe_2(SO_4)_3.$$

The fact of such an equilibrium was proved by adding a little KSCN. A red color developed, showing the presence of ferric iron and a white cuprous sulphocyanide was precipitated. The depth of color due to $Fe(SCN)_3$ was compared with the colors produced from known solutions of $FeCl_3$. It was thus found that when the cupric salt was 0.001 normal, and ferrous salt 0.02 N, the concentration of the ferric salt was about 0.000001 N. This showed that the equilibrium at ordinary temperature is chiefly displaced towards the left—in short that ferrous sulphate and cupric sulphate are compatible. Nevertheless, the products were present in slight amount and the equilibrium could be further displaced to the right by warming. As a matter of fact cuprous sulphate is not a stable salt, decomposing into metallic copper and cupric sulphate. Stokes showed that at 200° the equilibrium is wholly displaced towards the right.[1] The compatibility of any of the metallic salts concerned in ore deposition with such other salts as are likely to be present demands detailed investigation.

In reference to Weed's statement which Ransome quotes (p. 208) "enrichment is largely dependent upon the presence of marcasite, pyrite or some other form of iron sulphide in the primary ore, since lixivation depends upon the iron sulphate and precipitation is mainly effected by the unaltered sulphides" the key to deposition is suggested. Obviously as long as the solutions contain acid and active oxygen no deposition can occur. Pyrite has been shown to be particularly effective in concentrating copper. The removal of acid by processes of kaolinization with the wall rock, in certain vein enrichments, is an important method which W. H. Emmons has recently brought to my attention. By these and other influences the acid and oxy-

[1] ECON. GEOL., 1, 648.

gen which were present in the field of *solution* enter into chemical combination and the equilibrium readjusts itself with more or less precipitation of the valuable metal.

Both in the solution and precipitation of sulphides during processes of enrichment the tendency to fractionation which I have discussed in a previous paper[1] should be operative. The series of certain sulphides there noted in order of increasing solubility is: mercury, silver, copper, bismuth, cadmium, antimony, lead, zinc and ferrous iron. If a mixture of all of these sulphides began to be leached the last in the series would go first (except for specific influences, such as the insolubility of $PbSO_4$ or $ZnCO_3$); conversely if a mixture of salts of these metals came into contact with a precipitating sulphide the first of the series would be deposited first. The series ought therefore to represent roughly the order of arrangement of the sulphides with increase of depth in regions of leaching and enrichment, or at least in regions of slowly migrating solutions.

Another way in which chemistry may assist geology is in determining the stable state of an element or compound under definite conditions. For example chemistry would certainly suggest that most sulphides cannot be permanently stable in an oxidizing environment where leaching goes on. If they are found in the "upper zone" of an ore deposit it simply shows that sufficient oxygen has not yet reached them to decompose them. Of course, practically, a single crystal of a sulphide like pyrite enclosed in an igneous rock is exceedingly well protected from attack and moreover its oxidation is a very slow process at ordinary temperatures, but Ransome's statement that an ore body is never absolutely impermeable is applicable in this connection, so that, given sufficient time, the sulphides would be expected to disappear. Nevertheless, we find various sulphides, *e. g.*, chalcocite and chalcopyrite recorded as having been "noted" in the oxidizing zone.[2]

Such minerals would appear to be primary with respect to the

[1] Econ. Geol., 1910, 5, 1–14.

[2] See "A Genetic Classification of Minerals," W. H. Emmons, Econ. Geol., 1908, 3, 611–27.

secondary alteration products and owe their persistence only to their slow rate of attack compared to the surrounding rocks. It is questionable whether they should be suggested as *genetically* related to the oxidation zone. This is a difficulty inherent in "classifications." For example the seventh class in Mr. Emmons's classification just cited, is "Secondary Minerals in Zones of Oxide and Sulphide Enrichment." From either a chemical or a genetic point of view this class would appear to be too large, and might well be subdivided into minerals of an oxidized zone and minerals of a reduced zone, or minerals of the zone of secondary enrichment. In such classes, then, should be placed only minerals *originating* or *stable* under these conditions. If such a table could be made out it might be much easier under a given set of conditions to diagnose a mineral as "primary" or "secondary."

ROGER C. WELLS.

Sir:—The very interesting article by Mr. F. L. Ransome on "Criteria of Downward Sulphide Enrichment"[1] has suggested the following discussion from the standpoint of physical chemistry.

Mr. Ransome states (p. 209), quoting Lindgren, that covellite (CuS) is the only sulphide peculiar to the lower ground water zone of sulphide enrichment. The chemical behavior of cupric sulphide tends to confirm the conclusion, first, that it could not be formed below at high temperatures as a primary mineral, and second that it would not be a stable mineral if once formed in the upper oxidized zone. As evidence that it cannot be formed at high temperatures is the well-known qualitative fact that cupric sulphide dissociates on heating, forming cuprous sulphide. This behavior has been investigated quantitatively very recently by Wassuchnow[2] who has found that at temperatures slightly above the boiling point of sulphur (445°) the dissociation pressure of cupric sulphide increases with enormous rapidity, so that at 500° the dissociation pressure is sev-

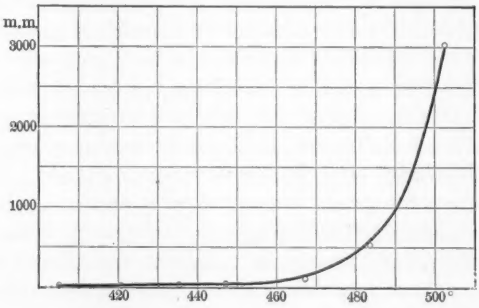
[1] ECON. GEOL., 5, 205, 1910.
[2] Dissertation, Berlin, 1909.

eral atmospheres. In the table, the results obtained by Wassuchnow have been recalculated to show the dissociation pressures in millimeters of mercury at various temperatures. The pressures were calculated, assuming that the average molecular weight of sulphur vapor, which is 170 at 445°, does not change with the temperature. This is not quite true but represents the closest approximation that can be made at present. Above 445°, the pressure undoubtedly increases somewhat faster than the results indicate, due to increasing dissociation of sulphur vapor.

DISSOCIATION PRESSURES OF CUPRIC SULPHIDE.

Temperature (o° C.).	Pressure (mm.).
405	1.3
421	4.0
436	12.2
447	28.4
467	129.
484	527.
502	3040.

These results are plotted in the figure. Unless the pressure of sulphur vapor were greater than the dissociation pressure at a given temperature, cupric sulphide would decompose, forming



chalcocite, which makes it appear certain that covellite could not be formed at high temperatures.

When prepared in the laboratory by wet methods, cupric sulphide is not in the least a stable compound, oxidizing readily to

the sulphate when moist and usually containing an admixture of cuprous sulphide and sulphur. This tendency to form the soluble sulphate would probably prevent the mineral from forming in a zone where oxidation is possible, limiting its formation as Ransome states.

In connection with Mügge's work on quartz mentioned by Ransome (p. 213) the recent work of Wright and Larsen[1] should be mentioned. They have examined a considerable number of quartzes occurring in different kinds of rock and have found that vein and geode quartz and some pegmatite quartz has formed below 575°, while quartz in granite and porphyry was formed above this temperature. The determinations were made on thin sections under the microscope. Quartz formed at high temperatures always contains numerous minute fractures due to its change in crystal form below the inversion temperature (575°) and if some test for minute cracks in a hand specimen were devised, it would perhaps contribute considerably toward determining the temperature to which a given sample of quartz had been subjected. Possibly the ink test mentioned by Mr. Ransome (p. 217) could be applied.

Aragonite is apparently not a common mineral in ore deposits but it may be of interest to call attention to its relation to calcite. It is unstable compared with calcite through a great range of temperature—probably at all temperatures.[2] It passes into calcite rapidly when heated, as is well known, but the process is so slow at common temperatures that it practically ceases. The presence of aragonite would show that the temperature could not have been high since this mineral was formed.

Why aragonite should ever form in preference to calcite is difficult to understand though similar cases are not uncommon. Rapid crystallization very often induces at first an unstable form of a substance, in fact this is so common an occurrence in the laboratory as to form the rule rather than the exception, a fact which was first stated by Ostwald. So calcium carbonate when precipitated rapidly from a hot solution forms aragonite. The

[1] *Amer. Jour. Sci.* [4], 27, 421, 1909.
[2] *Zeit. phys. Chem.*, 33, 740, 1900.

deposit of calcium carbonate about hot springs consists of this mineral as does artificial calcium carbonate when prepared in this manner. The formation of large clear crystals of aragonite, however, which must have formed slowly, cannot be accounted for in this manner. In some cases, it is very probable that traces of a substance isomorphous with aragonite, such as strontianite ($SrCO_3$) or cerussite may determine the crystal form. It would be interesting to know whether traces of these or of similar substances may not be generally present in well crystallized aragonite.

From a chemical standpoint it is difficult to see why kaolin should be limited to the oxidized zone and the zone of sulphide enrichment (p. 212, quoted from Lindgren). There is no process of oxidation involved in its formation from other silicates, but rather one of hydrolysis involving double decomposition with water. This process is very much hastened and made more complete by high temperature. There are many salts which are slightly hydrolyzed under ordinary conditions of temperature but which are very largely hydrolyzed when heated with water under pressure at high temperatures. It would seem rather that the presence of kaolin would indicate merely that water had been present. The kaolin should form much more rapidly in a deep zone at high temperature provided water is present than it does on the surface. Feldspar is attacked very appreciably by water at high temperature in a comparatively short time. Mr. N. A. Martin carried out some experiments on this subject under my direction several years ago, but the results have not been published. He found that finely powdered feldspar heated for some hours at approximately 200° in a sealed tube yielded a considerable quantity of material which was readily soluble in acids. Probably the reason why kaolin occurs more particularly in the oxidized zone and the zone of sulphide enrichment is because, in the deeper rocks, water cannot penetrate. Certainly if it penetrated it ought to form kaolin more rapidly than near the surface at a lower temperature.

Regarding wall rock alteration induced by descending solutions (p. 216), perhaps the chief change to be expected would

be the replacement of more soluble compounds by more insoluble ones containing part of the original components. Thus pyrite would be converted by solutions containing copper into a copper sulphide or a copper and iron sulphide, and anglesite would form cerussite, which is more insoluble, by means of water containing calcium bicarbonate in solution, just as in the laboratory barium carbonate can be converted into barium sulphate by means of a soluble sulphate.

H. W. FOOTE.

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Sir:—The article of Mr. F. L. Ransome[1] describing the criteria of downward sulphide enrichment is one which is very suggestive to any person who has studied such enriched ore deposits in the field. I shall attempt no criticism of the paper, but wish to offer the following comments chiefly based on conditions at Butte, Montana.

In the copper mines of Butte it has long been recognized that chalcocite is largely if not wholly of secondary[2] origin. Mineral specimens indicate that the precipitation of chalcocite is most commonly produced by iron sulphide but may also be produced by galena or sphalerite, and perhaps by other sulphides. It has also been recognized that covellite, so far as known at present, is secondary. Enargite has been thought to be in large part primary, and this conception is in harmony with the report that the amount of enargite in the ore seems to be increasing with depth, as judged by the arsenical content of the smelter fumes. It is also true that in cases of incrustation of one sulphide mineral by one or more others enargite is frequently the innermost mineral. In some cases it is completely incrusted by a layer of chalcopyrite which in turn is coated with chalcocite. Bornite probably occurs to some extent as a primary constituent, but for

[1] F. L. Ransome, "Criteria of Downward Sulphide Enrichment," ECONOMIC GEOLOGY, Vol. V., 1910, p. 205.

[2] I shall in these comments use the term primary for those minerals formed before the period of downward sulphide enrichment, and the term secondary for minerals formed during that period.

the most part is another one of the minerals of secondary enrichment. According to the conception of R. H. Sales, bornite may be formed, and re-dissolved, and formed again, several times in cyclic fashion by the processes of secondary enrichment, combined with fluctuations of ground water level due to irregular rainfall and erosion. Chalcopyrite occurs in the Butte mines probably both as a primary constituent and also as a secondary sulphide. Thus, according to microscopic studies,[1] it is intimately associated with pyrite and bornite, and in some mineral specimens it has been found as coatings upon covellite. It occurs in the gold-silver veins in irregular bunches, whose distribution and size are also irregular, but since they show no zonal distribution the sulphide in them is probably primary.

In regard to minerals of the gangue which may be considered as strong evidence of the existence of the process of secondary enrichment, Mr. Ransome has mentioned alunite. In the Butte mines alunite is not known to occur, but another mineral does occur which is equally significant. It is gypsum. Inasmuch as gypsum is known to be decomposed at about 150° C., and even perhaps at as low a temperature as 120° C.,[2] it is clear that it must be formed at low temperatures. Furthermore, it is one of those minerals which is produced by the reaction of sulphuric acid upon minerals containing calcium. And inasmuch as sulphuric acid is practically always present in processes of sulphide enrichment, gypsum is to be expected unless calcium is very deficient. As a matter of fact, gypsum is very uncommon in the Butte mines, and especially in the sulphide zone, but occurs in some of the mine workings located on the gold-silver veins. It is undoubtedly forming at the present time in places where secondary enrichment is still in progress. Gypsum is not a normal product of vein formation. This fact is probably also due to the low temperature at which it is produced. During primary filling of veins the solutions active are usually at moderately high temperatures and therefore produce no gypsum. If they become cooled so as to form gypsum, it will be produced

[1] J. F. Simpson, ECON. GEOL., Vol. 3, 1908, p. 628.
[2] A. E. H. Tutton, *Proc. Roy. Soc.*, A, LXXXI., 1908, p. 40.

probably only at or very near the surface, and gypsum formed in this way will be removed very promptly by erosion.

Evidences of the process of secondary enrichment are of course much easier to find in districts where it is still in progress than in regions where the process is no longer active. Thus at Butte the existence of sulphuric acid in the mine waters is itself very good evidence of the process of secondary enrichment. Further, the formation of other sulphates in addition to gypsum in the mine galleries is evidence of the same process. Thus chalcanthite has been formed in great abundance in some of the mine galleries. Again, melanterite has been produced at other points; and, finally, in some places where the copper veins are close to gold-silver veins goslarite is being produced in the mine galleries.

The existence of alunite, gypsum and other sulphates is, of course, not in itself proof of the existence of secondary sulphide enrichment. It is proof only that sulphated waters are or were active at the locality. When such waters are of meteoric origin they nearly always owe their sulphur content to the oxidation of sulphides of iron. Under such conditions, if sulphides of copper, lead or zinc occur in association with the sulphide of iron they will be more or less enriched by secondary concentration due to the action of the sulphated waters.

Mr. Ransome remarks that quartz of original vein formation can not be distinguished from secondary quartz. This is true only in those cases in which the temperature of formation of the primary quartz was less than 575° C. But since such cases are more common than vein quartz produced at higher temperatures the distinction between the original and the secondary quartz can rarely be made. In this connection it may be pointed out that the data furnished by Le Chatelier[1] on the volume change at inversion, and by White[2] on the latent heat of inversion, make it possible to calculate to what extent the temperature of inversion is modified by pressure. Thus, from the formula of James Thomson, which may be written as suggested by Harker[3] as follows:

[1] Le Chatelier, *Bull. Soc. Min. France*, Vol. 13, 1890, p. 112.
[2] White, A. P., *Am. Jour. Sci.*, Vol. 27, 1909, p. 435.
[3] A. Harker, "Natural History of Igneous Rocks," 1909, p. 163.

$$\frac{dT}{dp} = 0.0242 \frac{T}{L}(v_2 - v_1);$$

we have by substitution:

$$\frac{dT}{dp} = \frac{0.0242 \times 848 \times 0.0143}{4.3 \times 2.58} = 0.02645.$$

That is to say, an increase of pressure of one atmosphere raises the temperature of inversion 0.02645° C. Further, since 13 feet of depth produces approximately 1 atmosphere of pressure, the inversion point at 1,300 feet of depth is raised about 2.5° C., and at 2 miles the inversion point is raised about 21° C.

ALEXANDER N. WINCHELL.

UNIVERSITY OF WISCONSIN,
May 15, 1910.

THE DISSEMINATED LEAD DEPOSITS OF S. E. MISSOURI.

DISCUSSION OF REVIEW BY F. L. RANSOME.

Sir:—I regret that the review of the "Disseminated Lead Deposits" should have impressed Dr. Buckley as in anyway unfair. Where merit and defect are impartially pointed out, it is perhaps inevitable that the reader should give undue weight to the latter. Consequently, while I cannot retract adverse criticism of the plan and execution of the report, it is quite possible that the discussion of these blemishes may have given a more unfavorable color to the whole review than was intended. Without going into details, I therefore willingly repeat with emphasis my appreciation of the importance of Dr. Buckley's contributions to Missouri geology, of the real value of the work reviewed, of the thoroughness of the observations recorded, and of the general soundness of the conclusions. It is but fair to remember, also, that some of the defects to which attention was called may in this case be judged with more leniency than could be accorded volumes published under trained editorial supervision and printed by specially skilled workmen.

F. L. RANSOME.

ON THE DEVELOPMENT OF THE ANTICLINAL THEORY.

DISCUSSION OF PAPER BY M. J. MUNN.

Als Vater der Antiklinaltheorie gestatten Sie mir einige Bemerkungen zu *Malcolm J. Munn's* Antiklinalstudien.

Wir in Europa verstehen unter der Antiklinaltheorie die *Tatsache,* dass die meisten der ergiebigen Erdöllagerstätten in oder nahe dem Rücken der Antiklinalen, Dome oder Monoklinalen liegen. Ich fand dies zuerst (1876) in Pennsylvanien und Canada dadurch, dass die lineare Erstreckung dieser Ölfelder parallel zu den intensiver ausgeprägten Antiklinalen des Chestnut und Laurel ridge sind, wie ich dies Lesley's geologischer Karte von Pennsylvanien entnahm. Meine Untersuchungen der Ölfelder bestätigte die Vermutung, ich fand in den oilfields in der Tat die Antiklinalen.[1] Die Antiklinaltheorie ist somit nicht auf induktiven, wie *Munn* meint, sondern auf deduktiven Wege entstanden; ich habe damals keine Erklärung dieser Tatsache gegeben, die erst von anderer Seite versucht wurde. Der Werdegang der Antiklinaltheorie ist also ganz entgegengesetzt von jener, wie ihn *M. J. Munn* auf Seite 512 der Economie Geology Vol. IV. annimmt. Der Erdölgeologe Pennsylvaniens *C. Carll* lehnte jedoch meine Antiklinalhteorie ab und *Ch. Ashburner* wollte sie nur für einzelne Fälle gelten lassen; hingegen traten *I. C. White* mit *Earseman* später *H. M. Chance* und *E. Orton* für dieselbe auf Grund ihrer reichen Erfahrungen ein. In Europa fand sie schon früher (1879) ihre eifrigen Verteidiger, so in *Paul* und *Tietze* für die Karpaten.

Als ich Nordamerika im Jahre 1876 bereiste, war kurz zuyor der ausgezeichnete Spezial Report on the Petroleum of Pa. von *Henry E. Wrighley* erschienen, in welchen er auf Seite 42 den Zusammenhang der Öllinen mit den Antiklinalen bestritt. Es war mir durch viele Jahre unklar gegen wen hiemit polemisiert werdensoll, ich vermutete gegen manche Oilmen. Erst vor wenigen Jahren fand ich, dass bereits 1861 *E. B. Andrew*

[1] Höfer, "Petroleumindustrie Nordamerikas," 1877, pp. 81, 82.

und der geniale Forscher *T. Sterry Hunt* jenen Zusammenhang für die nordamerikanischen Ölvorkommen erkannten, was jedoch von den speziellen Ölgeologen abgelehnt und zur Vergessenheit verurteilt wurde. Die beiden Genannten sind im Vereine mit *Oldham* die Grotsväter der Antiklinaltheorie. Nur *T. St. Hunt* gibt auch eine Erklärung der Antiklinaltheorie unter Hinweis auf die verschiedenen Dichten von Wasser und Erdöl; doch auch er hatte zuerst die Tatsache festgestellt und gab dann erst eine Erklärung derselben.

Die Antiklinaltheorie als *Tatsache* hat sich erst dann freie Bahn geschaffen, als ihre Richtigkeit auch in fast allen Erdölgebieten der Erde bewiesen wurde und die reichsten Früchte trug.

HANS HÖFER.

LEOBEN, 12 Mai, 1910.

REVIEWS

The Question of the Origin of the Iron Ores in the Older Pre-Cambrian Series of Sweden. By H. SJÖGREN. Geol. Fören. Förhandl., Vol. 30, pp. 115–155, 1908.

Discussion regarding the origin of the Swedish iron ores continues in the Geological Society of Sweden, but it can not be said that opinion is unanimous. The hypothesis of the sedimentary origin of the ores, for many years almost universally held, has had an unfavorable effect upon the progress of investigation, but in the last decade a marked change is apparent. A few years ago H. Johansson[1] began a series of important articles in which he attempted to prove the magmatic origin of all of the Swedish iron ores. The author of the paper here reviewed deals with these same questions and explains that, although he appreciates these articles greatly, he finds himself unable to accept all of the conclusions of Johansson. The younger pre-Cambrian formation includes, according to the author, the clay slates and quartzites which occur in several places and which are separated from the older gneisses and granulites by a clear unconformity. The middle Swedish iron ores generally belong to the older pre-Cambrian, while those of the type of the deposit at Kiruna and Gellivare belong to the younger pre-Cambrian series.[2]

The author agrees with Johansson in believing the old sedimentary view of origin to be entirely unsatisfactory. His own observations have led him to the conclusion that the ores are epigenetic, that their tendency is to appear at contacts, and that they were formed at great depth under anamorphic conditions, since the folding of the pre-Cambrian strata. Finally, he believes that the iron ores were formed by aqueous magmatic solutions which, on one hand, may grade into ordinary solutions and on the other hand into magmatic segregations. It is thus easy to understand the occurrence of these iron ores both in rocks of magmatic and of sedimentary origin. In the one case the magmatic solutions have broken their way through recently consolidated or semi-consolidated rocks; in another case they have penetrated crystalline schists and have transformed these without change

[1] *Geol. För. För.*, Vol. 28, pp. 516–538, and Vol. 29, pp. 143–186 and 285–300.

[2] See also "The Geological Relations of the Scandinavian Iron Ores," *Trans. Am. Inst. Min. Eng.*, Vol. 38, 1907, pp. 877–946.

of structure to ores; in a third case they have searched out easily replaceable limestones. Among the objections to Johansson's magmatic theories is cited the fact that he is forced to appeal to a hypothesis of magmatic origin of the ore-bearing limestone.

According to the author's view it is probable that some of the iron ores, for instance those of the Kiruna, Gellivare and Grängesberg districts, are magmatic segregations. But even so they may not have originated exactly as explained by Johansson. In the case of titaniferous ores connected with basic eruptives the differentiations effected at the present place of the ore are with good reason separated from those effected at greater depth in the magma basin and whose products were carried up by separate acts of eruption. The apatite ores are rather comparable to the second of these types.

The author believes that the apatite ores were formed from solutions containing so small a quantity of water as to be rather aqueous magmas than water solutions. The quartz-feldspar ores have been deposited from more dilute solutions, which could spread in the surrounding rocks replacing them metasomatically by ore minerals with retention of their granular or schistose structure. The formation of the limestone ores and the "skarn" ores took place in a similar manner accompanied by the development of the characteristic mineral association of garnet, epidote, etc.

The origin of the banded "dry ores" is more doubtful, but probably is similar to that of the other ores. The explanation of the quartz streaks as planes of sedimentation is hardly satisfactory and the author is inclined to follow Johansson is ascribing the lamination "to some phenomenon of purely physico-chemical nature." In several ores of Lofoten, Norway, which appear in typical granites and for which a sedimentary origin is out of the question, a similar banded structure appears.

Mr. Sjögren believes that Johansson has gone too far when he insists that one principle only can account for the genesis of all iron ores in the southern regions of Sweden and that he does not fully appreciate the changes which the ores have undergone in connection with their ascent from a deep-seated zone to a level near the present surface. Johansson even goes so far as to consider the chlorites developed in zones of disturbances as products of magmatic differentiation. With good reason the author objects to this.

A fundamental problem remains of course in the interpretation of the pre-Cambrian crystalline schists. These crystalline schists in the Swedish pre-Cambrian areas were for a long time considered of sedimentary origin. In late years, however, the opinion has gained ground that they are largely igneous rocks subjected to regional metamorphism and that only a comparatively small proportion are actually sediments.

At the present time almost all of the Swedish gneisses, as well as most of the granulites and "hälleflintas," are considered as igneous rocks partly intrusive, partly effusive; a few enfolded remnants of sedimentary rocks are represented by quartzites, quartzitic mica schists, and limestone.

Most of the iron ores of middle Sweden are connected with "granulites," which are essentially fine-grained, sometimes schistose, rocks consisting of quartz and alkali feldspar associated with some basic varieties. Both Törnebohm and Johansson have pointed out the high degree of differentiation possessed by these granulites as shown by the absence of rocks of intermediate composition. Although iron ores appear outside the granulitic terranes, such bodies are exceptional and have neither the size nor the importance of those within the granulite. The older sedimentary hypothesis has generally been abandoned, although Professor Holmquist in a recent paper still regards them as tuffs or detritus of volcanic rocks and interprets their parallel structure as stratification. Johansson and others believe that the granulites are intrusive rocks and represent several chemical types which are also present in the Swedish granites.

Johansson sees in the characteristic granulitic structure the result of a mechanical churning of the magmas during their period of liquation and thinks that this process greatly facilitated the separation of the products of differentiation. He thus advocates magmatic differentiation with simultaneous mechanical deformation as the cause both of the development of the granulite as well as that of the ores. In this connection the latest results of geological reëxamination of the famous granulite region of Saxony is of interest.[1] This region, according to these results, does not consist of Archean schists, regionally metamorphosed, but is a laccolith of Paleozoic age which has domed and metamorphosed the overlying Devonian sediments. The extreme differentiation within the Saxon granulite recalls the similar differentiations in the middle Swedish granulites, besides the prevailing quartz-orthoclase granulites dark rocks are also found in Saxony which are termed pyroxene granulite and which have a petrographic composition corresponding to hypersthene norite. Locally this changes to a pyroxene rock, sometimes containing garnets, consequently to a rock which reminds one of many of the Swedish "skarns." Credner, as well as Johansson, believes that the parallel structures so prominent in the granulites are caused by pressures and movements within the still fluid magma and both believe that these mechanical forces promoted the differentiation.

Sjögren, however, inclines to the belief that the granulites include

[1] Credner, H., *Centralblatt für Mineralogie*, 1907, p. 513.

both intrusive and effusive eruptives, as well as some chemical and clastic sediments, all of which have been subjected to a certain kind of metamorphism which has produced their structural peculiarities. The conditions which obtained are not wholly clear; the ordinary regional metamorphism appears insufficient to explain facts such as the development of narrow, often contorted, zones, the surroundings of which may be unaffected by metamorphism. The structure of the granulites is not cataclastic, but must have resulted from complete re-crystallization, probably in the zone of rock flowage. It is likely, according to Sjögren, that the magmatic waters which accompanied the granitic intrusion were an important factor in the re-crystallization of the granulite as well as in the formation of the ores. He, therefore, connects the granitic intrusion genetically both with the formation of granulites and with that of the ores. This view differs, therefore, considerably from that of Johannson.

Johansson desires to derive from the limits of stability of the minerals the temperature of formation of given mineral associations. The temperature of fusion is regarded as a characteristic upper limit of stability, and the following scheme is proposed:

1. Magmatic high temperature zone.
   (*a*) The peridotite zone.
   (*b*) The gabbro zones.
2. Magmatic low temperature zone.
   (*a*) The syenite zone.
   (*b*) The granite zone.
3. Zone of magmatic after-actions.
   (*a*) Zone of the ore veins.
   (*b*) Zone of the zeolites.
4. The superficial zone.

For the high temperature zone the lower limit is determined by the fusion of plagioclase and rhombic pyroxene placed at 1200° or 1300° C. For the lower limit of the interval of crystallization of the syenite magma the minimum of temperature of fusion of the alkali feldspars are given at about 1000°. Sjögren points out that this reasoning is incorrect, simply because the points of fusion do not correspond to the temperature of crystallization, and that for a great number of minerals the limits of stability are materially changed during dynamic conditions. He believes that in certain basic intrusions a concentration of ore minerals took place simultaneously with the dynamo-metamorphism. Diabases and gabbros have been transformed to amphibolites or chloritic schists and the contained iron or copper has often separated out as sulphides, as, for instance, in the "fahlbands." By this process, based on the so-called Riecke's principle, the small grains of ore become

enlarged at the expense of the smaller. Neither does Johansson take any account of the aqueous magmas such as formed the pegmatite for instance. The scheme presented by him is really only a limited special case which is entirely apart fromt the conditions obtaining when the iron ores were formed; Sjögren points out that it is necessary to study the conditions of equilibrium at high temperatures and pressures in the presence of water. While Johansson believes that the ores crystallize simultaneously with the surrounding minerals and that the ores, therefore, are syngenetic with these rocks the author's conception leads to an opposite result, namely, that the ores are epigenetic. According to Johansson the peridotite zone ranges from 1400° to 1700° C.; the gabbro zone from 1200° to 1500° C.; the syenite zone from 1000° to 1300° C.; the granite zone from 600° to 1000° C. The temperatures of fusion, according to Brun, are as follows: Chromite 1670° to 1850°; titanic iron ore ($Fe_2O_3 + 3FeTiO_3$) 1450°; specularite 1300°; magnetite 1260°. The chromite corresponds to the peridotite zone as well as the titanic iron ore to the gabbro zone because both are products of differentiation in the corresponding rock, but, on the other hand, the points of fusion of magnetite and specularite are high above the temperature of crystallization of the granitic magmas with which these ores are genetically connected. From this Sjögren concludes that the relations of magnetite and specularite to the surrounding quartz, feldspar rocks (gneisses and granulites) is different from the relation of chromite to peridotite and of titanic iron ores to gabbros.

A similar result is obtained from a review of the fusion temperature of the gangue minerals. The rhombic and monoclinic pyroxenes are typical gabbro minerals and their points of fusion, about 1130°–1280° C. agree with this. The amphiboles which are characteristic gangue minerals, also fuse between 1100° and 1200° and fall, therefore, within the syenite zone. While, therefore, the pyroxenes belong to the gabbro zone and the amphiboles to the syenites, they are associated with iron ore within the granite zone, which has a temperature of crystallization between 700° and 1000°. The fact that the gangue minerals have such a high temperature of fusion compared to the surrounding rocks shows that they did not crystallize from magmas in dry fusion, but from aqueo-igneous solutions whose temperature of crystallization has been lowered by the water which they contain.

Under the same relations have crystallized the other gangue minerals like garnet, wollastonite, biotite, muscovite, epidote, and chlorite; part of them indeed contain hydroxyl, showing that they were formed in presence of water.

W. LINDGREN.

Zur Kenntnis der wasserhaligen und wasserfreien Eisenoxydbildungen in den Sedimentgeslein. By H. STREMME. Zeit. f. prakt. Geol., XVIII., 1, pp. 18–23, 1910.

It is well known that under ordinary conditions iron oxide is precipitated from solutions in a hydrous colloidal form. H. Stremme has summarized both the laboratory and field data relating to the later dehydration of the iron oxides. The possibility of the direct precipitation of the anhydrous form is also discussed.

According to the writer the known experimentally tested factors favoring dehydration are: dryness, high temperature, high pressure, salt content of solution and acid content of solution, *e. g.*, CO_2.

The salt and acid content apparently influence the degree of hydration of the iron oxide by lowering the vapor pressure of the solution. Each iron hydrate is supposed to have its own vapor pressure, which is the minimum pressure of water vapor with which the hydrate can remain in equilibrium at any given temperature. More exact data than those given by the writer are to be desired on this subject. On account of the small vapor pressure of the hydrated iron oxides, as compared with that of water, the concentration of salt must be high if it is the sole factor in producing dehydration. No systematic study has yet been made of the effect of CO_2 on the dehydration of the iron hydrates, but tests with CO_2-bearing springs seems to show that it is more effective than salt. Pressure in a closed vessel does not cause dehydration, since the iron hydrate is of smaller molecular volume than that of its two components, iron oxide and water, when separated. Red color is, of course, characteristic of the anhydrous oxide.

Various occurrences of natural deposits with a red color are discussed and the dehydrated condition of the iron oxide is explained as follows: In the red earths of arid regions by desiccation and relatively high temperature; in certain spring deposits by high content of salt and CO_2; in formations containing gypsum by high salt content present during deposition; in the red muds of the deep sea, and in certain marine iron ores by salt content and high pressure, principally the latter.

J. D. TRUEMAN.

Iron Formation of Woman River Area. R. C. ALLEN. Eighteenth Annual Report of the Bureau of Mines, 1909, Ontario.

The Woman River area embraces a number of pre-Cambrian iron formation belts, about twenty miles north of Ramsay station, on the Canadian Pacific Railroad, in the Sudbury Mining Division of Ontario. The area covered by Allen lies west of Rush Lake.

The succession is as follows:

Basic Igneous Dikes, } Relative ages not known.
Mica Porphyry, }
Acid Igneous Rocks—Extrusive and intrusive.
Iron Formation,
Basal Greenstones.

The series has been intensely folded and extensively brecciated. The strike of the iron formation banding is N. 45° E., but is in some places at right angles to this direction where modified by cross folding. Everywhere the rocks stand practically on edge. The basal greenstones and the iron formation are intruded by a great many basic and acid dikes, the latter showing gradation into an acid volcanic breccia overlying the iron formation.

The various phases of the iron formation are: (1) Finely banded cherty carbonates, (2) hematitic, magnetic, pyritic, cherts, (3) black and red jaspilites, (4) a unique amphibole-magnetite rock, in which the petrographic character of the amphibole suggests riebeckite and (5) iron ore. The cherty iron carbonates are regarded as the source of the other iron-bearing rocks, although the possibility that some of the varieties may be partly original is not denied. The derivation of the secondary varieties is ascribed to the same katamorphic and anamorphic processes by which Van Hise has explained the origin of similar derivatives in the other iron formations.

The distribution of the iron ores bears no relation to the present structural features of the formation nor to its present erosion surface.

The relation of the iron formation to the associated igneous rocks is expressed by the following statements: The iron formation is sedimentary; it conformably overlies the ellipsoidal greenstones, in that no period of subaerial erosion intervened between the deposition of the iron formation and the greenstone; the iron formation and the overlying volcanic breccia and rhyolite orphyry are also conformable. The evidence of the sedimentary origin of the iron formation consists in its banding, the iron carbonate content, and the parallelism of the individual bands to each other and to the basal plane.

The evidence for conformity with the basal greenstone lies in the parallelism of the banding of the iron formation with the plane of contact with the greenstone, the absence of detrital material and the probable subaqueous origin of the ellipsoidal greenstones. The conformity of the iron formation and the overlying acid igneous rocks appears probable but is not supported by many field observations, owing to the sparsity of exposed contacts. Wherever observed, the contacts are sharp and show no detrital materials.

From field relations of the iron formation to igneous rocks in the

Woman River and other areas but mainly from unpublished work of Leith, Allen believes that the genesis of the iron formations was related to igneous rather than sedimentary agencies and processes. He interprets the physical history of this area to be extrusion of basic greenstones upon a submerged floor, rapidly followed by the precipitation of iron formation, contributed from magmatic solutions, without the intervention of clastic sedimentation. The precipitation of the iron formation was followed by the extrusion of acid igneous rocks. The three rock types, however, basal greenstone, iron formations and acid igneous rock are perhaps differentiates of one parent magma.

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